Lepton flavor violation beyond the MSSM

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Abstract

Most extensions of the Standard Model lepton sector predict large lepton flavor violating rates. Given the promising experimental perspectives for lepton flavor violation in the next few years, this generic expectation might offer a powerful indirect probe to look for new physics. In this review we will cover several aspects of lepton flavor violation in supersymmetric models beyond the Minimal Supersymmetric Standard Model. In particular, we will concentrate on three different scenarios: high-scale and low-scale seesaw models as well as models with R-parity violation. We will see that in some cases the LFV phenomenology can have characteristic features for specific scenarios, implying that dedicated studies must be performed in order to correctly understand the phenomenology in non-minimal supersymmetric models.

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1 Introduction

The Standard Model (SM) particle content has been recently completed with the discovery of the long-awaited Higgs boson at the CERN Large Hadron Collider (LHC) [1,2]. This constitutes a well deserved reward after decades of intense search, with great efforts from the theory and experimental communities. Furthermore, it also confirms that the SM must be, at least to a good approximation, a precise description of nature up to the energies explored. In fact, and apart from some phenomenological facts that indeed require some unknown new physics (NP), like the existence of dark matter and neutrino masses, the SM explains to a high level of accuracy all the observations made in a wide variety of experiments.

For the last decades, the progress in theoretical particle physics has been driven by naturalness considerations in the form of the famous hierarchy problem. This has led to many extensions of the SM, all of them attempting to explain why the weak scale has not been pushed to much higher energy scales by some hypothetical NP degrees of freedom. Among the many proposals to address this issue, supersymmetry (SUSY) is certainly the most popular one. However, and similarly to other analogous solutions to the hierarchy problem, the predicted new particles at the weak scale have not been observed at the LHC.

This has of course raised some doubts about the existence of supersymmetry close to the weak scale. Since this proximity is to be expected in case supersymmetry has something to do with the hierarchy problem, the whole idea of weak scale supersymmetry is under some pressure at the moment. However, it is worth keeping in mind that most experimental searches for SUSY focus on the Minimal Supersymmetric Standard Model (MSSM). This model, which constitutes the minimal extension of the SM that incorporates SUSY, has some underlying assumptions that lead to very specific signatures. For example, in the MSSM one assumes the conservation of a discrete symmetry, known as R-parity [3, 4], which forbids all renormalizable lepton and baryon number violating operators and leads to the existence of a stable particle, the lightest supersymmetric particle (LSP), which in turn leads to large amounts of missing energy in supersymmetric events at the LHC. There are, however, many known (and well motivated) supersymmetric scenarios with R-parity violation and, in fact, several authors have shown that simply by allowing for non-zero B-violating terms in the superpotential, the current LHC bounds can be clearly relaxed, allowing for the existence of light squarks and gluinos hidden in the huge QCD background [5,6]. Similarly, one can extend the MSSM in many other directions, often changing the phenomenology at colliders dramatically. This suggests that it might be too soon to give up on SUSY, a framework with many possibilities yet to be fully explored.

As explained above, there are some well-grounded phenomenological issues that cannot be explained within the SM. One of these open problems is the existence of non-zero neutrino masses and mixings, nowadays firmly by neutrino oscillation experiments [7–9]. In fact, this issue is not addressed in the MSSM either, since neutrinos remain massless in the same way as in the SM. This calls for an extension of the MSSM that extends the lepton sector and accommodates the observations in neutrino oscillation experiments. This can be done in two different ways: (1) high-energy extensions, in which the new degrees of

freedom responsible for the generation of neutrino masses live at very high energy scales, and (2) low-energy extensions, with new particles and/or interactions at the SUSY scale.

One of the most generic predictions in neutrino mass models is lepton flavor violation (LFV). In fact, neutrino oscillations are the proof that lepton flavor is not a conserved symmetry of nature, since neutrinos produced with a given flavor change it as they propagate. Therefore, all neutrino mass models built to give an explanation to oscillation experiments violate lepton flavor. However, we have never observed LFV processes involving charged leptons although, in principle, there is no symmetry (besides lepton flavor, which we know to be broken) that forbids processes like $\mu^- \to e^- \gamma$, $\tau^- \to e^- \mu^+ \mu^-$ or $K_L \to e^- \mu^+$. This fact can be well understood in some minimal frameworks, such as the minimal extension of the SM with Dirac neutrinos. In this case, LFV in the charged lepton sector is strongly suppressed, since neutrino masses are the only source of LFV, leading to unobservable LFV rates, like BR($\mu^- \to e^- \gamma$) $\sim 10^{-55}$ [10]. However, as soon as one extends the SM, this conclusion can be clearly altered [11,12]. In fact, new sources of LFV can be found in most extensions of the leptonic sector, either caused by new interactions, by new particles or even by complete new sectors that couple to the SM leptons.

After this discussion on LFV and neutrino masses a clarification is in order. Although neutrino oscillations imply LFV, LFV does not necessarily imply neutrino oscillations. There are models that predict charged lepton LFV without generating a mass for the neutrinos. The simplest example of this class of models is the general Two-Higgs-Doublet of type-III, where neutrinos remain massless but lepton flavor is violated due to the existence of off-diagonal $h - \ell_i - \ell_j$ vertices. Another relevant example is the MSSM itself, where neutrinos are also massless, but the slepton soft masses can induce LFV processes if they contain off-diagonal entries. One can actually estimate the branching ratio for the radiative LFV decay $\ell_i \to \ell_j \gamma$ as [13]

$$BR(\ell_i \to \ell_j \gamma) \simeq \frac{48\pi^3 \alpha}{G_F^2} \frac{|(m_{\tilde{\ell}}^2)_{ij}|^2}{M_{SUSY}^8} BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j), \qquad (1)$$

where G_F is the Fermi constant, α the fine structure constant, $(m_{\tilde{\ell}}^2)_{ij}$ are the dominant off-diagonal elements of the soft SUSY breaking slepton mass matrices and M_{SUSY} is the typical mass of the SUSY particles, expected to be in the TeV ballpark. This estimate clearly shows that rather small off-diagonal elements are required to satisfy the experimental bounds [14].

In general, one concludes that large LFV rates are expected in most models beyond the SM. This motivates the study of LFV as an indirect probe of new physics and, in particular, of supersymmetric models beyond the MSSM. This is the subject of this review ¹. In particular, we will concentrate on three different scenarios: high-scale and low-scale seesaw models as well as models with R-parity violation. As we will see, the LFV phenomenology turns out to be very different depending on the exact scenario, implying that lepton flavor

¹The field of lepton flavor violation beyond the MSSM has been intensely explored for many years and contains a vast literature. In this review I present my personal view of the subject and thus I must apologize for those papers which are not cited.

violation may be richer than in the MSSM. In some cases the common lore (established in the MSSM) turns out to be wrong, and specific studies must be performed in order to correctly understand the corresponding LFV phenomenology.

This review is organized as follows: in Sec. 2 we give an overview of the current experimental situation and briefly discuss some projects that will take place in the near future. Then we review the LFV phenomenology of three different types of models beyond the MSSM: high-scale seesaw models (in Sec. 3), low-scale seesaw models (in Sec. 4) and models with R-parity violation (in Sec. 5). Finally, we conclude in Sec. 6.

2 Current experimental situation and future projects

The search for LFV is soon going to live a *golden age* given the upcoming experiments devoted to high-intensity physics ². In addition to the LFV searches already taking place in several experiments, new projects will join the effort in the next few years.

In what concerns the radiative decay $\ell_i \to \ell_j \gamma$, the experiment leading to the most stringent constraints is MEG. This experiment, located at the Paul Scherrer Institute in Switzerland, searches for the radiative process $\mu \to e \gamma$. Recently, the MEG collaboration announced a new limit on the rate for this process based on the analysis of a dataset with 3.6×10^{14} stopped muons. The non-observation of the LFV process led to the limit $\mathrm{BR}(\mu \to e \gamma) < 5.7 \cdot 10^{-13}$ [18], four times more stringent than the previous limit obtained by the same collaboration. Moreover, the MEG collaboration has announced plans for future upgrades. These will allow to reach a sensitivity of about $6 \cdot 10^{-14}$ after 3 years of acquisition time [19]. This is of great importance, as this observable is the one with the largest rates in many models.

The most promising improvements in the near future are expected in $\mu \to 3\,e$ and $\mu - e$ conversion in nuclei. Regarding the former, the decay $\mu \to 3\,e$ was searched for long ago by the SINDRUM experiment [20], setting the strong limit BR($\mu \to 3\,e$) < $1.0 \cdot 10^{-12}$. The future Mu3e experiment announces a sensitivity of $\sim 10^{-16}$ [21], which would imply an impressive improvement by 4 orders of magnitude. As for the latter, several experiments will compete in the next few years, with sensitivities for the conversion rate ranging from 10^{-14} to an impressive 10^{-18} . These include Mu2e [22–24], DeeMe [25], COMET [26, 27] and the future PRISM/PRIME [28]. In all cases, these experiments will definitely improve on previous experimental limits.

The limits for τ observables are less stringent, although significant improvements are expected from B factories like Belle II [29, 30]. Finally, although the most common way to search for LFV is in low-energy experiments, colliders can also play a very relevant role looking for LFV processes at high energies. The LHCb collaboration reported recently the first bounds on $\tau \to 3\mu$ ever obtained in a hadron collider [31]. Furthermore, the CMS collaboration recently found an intriguing 2.4σ excess in the $h \to \tau\mu$ channel which translates into BR($h \to \tau\mu$) = $(0.84^{+0.39}_{-0.37})\%$ [32]. For reference, in Tab. 1 we collect

²See [15–17] for recent reviews.

LFV Process	Present Bound	Future Sensitivity	
$\mu \to e \gamma$	$5.7 \times 10^{-13} $ [18]	$6 \times 10^{-14} [19]$	
$\tau \to e \gamma$	$3.3 \times 10^{-8} $ [33]	$\sim 3 \times 10^{-9} \ [29]$	
$\tau \to \mu \gamma$	$4.4 \times 10^{-8} [33]$	$\sim 3 \times 10^{-9} \ [29]$	
$\mu \to eee$	$1.0 \times 10^{-12} $ [20]	$\sim 10^{-16} \ [21]$	
$ au o \mu\mu\mu$	$2.1 \times 10^{-8} \ [34]$	$\sim 10^{-9} [29]$	
$\tau^- \to e^- \mu^+ \mu^-$	$2.7 \times 10^{-8} \ [34]$	$\sim 10^{-9} [29]$	
$\tau^- \to \mu^- e^+ e^-$	$1.8 \times 10^{-8} \ [34]$	$\sim 10^{-9} [29]$	
au o eee	$2.7 \times 10^{-8} \ [34]$	$\sim 10^{-9} [29]$	
$\mu^-, \mathrm{Ti} \to e^-, \mathrm{Ti}$	$4.3 \times 10^{-12} \ [35]$	$\sim 10^{-18} \ [36]$	
$\mu^-, \mathrm{Au} \to e^-, \mathrm{Au}$	$7 \times 10^{-13} [37]$		
$\mu^-, Al \rightarrow e^-, Al$		$10^{-15} - 10^{-18}$	
μ^- , SiC $\to e^-$, SiC		$10^{-14} [38]$	

Table 1: Current experimental bounds and future sensitivities for the most important LFV observables.

present bounds and expected near-future sensitivities for the most popular low-energy LFV observables.

The theoretical understanding of all these processes will be crucial in case a discovery is made. With such a large variety of processes, the determination of hierarchies or correlations in specific models will allow us to extract fundamental information on the underlying physics behind LFV. This goal requires detailed analytical and numerical studies of the different contributions to the LFV processes, in order to get a global picture of the LFV anatomy of the relevant models and be able to discriminate among them by means of combinations of observables with definite predictions [39].

3 High-scale seesaw models

Neutrino mixing is, by itself, a flavor violating effect. Therefore, all neutrino mass models that aim at explaining the observed pattern of neutrino masses and mixings incorporate lepton flavor violation. However, specific predictions can be very different in different models.

Among the huge number of scenarios proposed for neutrino mass generation, the seesaw mechanism is arguably the most popular one. In its conventional form, the seesaw mechanism explains the smallness of neutrino mass by means of a very large energy scale, the seesaw scale M_{SS} , which suppresses neutrino masses as

$$m_{\nu} \sim \frac{v^2}{M_{SS}} \,. \tag{2}$$

Here $\langle H^0 \rangle = v/\sqrt{2} = 174$ GeV is the standard Higgs boson vacuum expectation value (VEV) that determines the weak scale. In order to obtain neutrino masses of about ~ 0.1

eV, one requires $M_{SS} \sim 10^{14}$ GeV. For this reason, this setup is usually called *high-scale seesaw*. The proximity of the high-energy scale M_{SS} to the grand unification (GUT) scale (as predicted in the MSSM) $m_{\rm GUT} = 2 \cdot 10^{16}$ GeV suggests an intriguing connection with unification physics, making the seesaw a very well-motivated scenario.

Regarding specific realizations of the seesaw mechanism, it is well-known that with renormalizable interactions only, three tree-level realizations exist [40]. These are usually called type-I [41–46], II [45–51] and III [52]. They differ from each other by the nature of the seesaw messengers: in the type-I seesaw these are singlet right-handed neutrinos, in the type-II seesaw scalar $SU(2)_L$ triplets with hypercharge two, and in the type-III seesaw fermionic $SU(2)_L$ triplets with vanishing hypercharge. In all cases they lead to a neutrino mass of the form of Eq. (2), where M_{SS} is proportional to the mass of the heavy mediators, and the induced neutrino masses are of Majorana type, thus breaking lepton number in two units.

Given the large Majorana masses of the seesaw mediators, one may wonder about how to probe the high-scale seesaw. In supersymmetric scenarios this is possible thanks to the sleptons. Even if their soft terms are flavor conserving at some high-energy scale, the renormalization group running down to the SUSY scale will induce non-zero off-diagonal terms due to their interactions with the seesaw mediators [53]. These can be probed since the misalignment of the slepton mass matrices with respect to that of the SM charged leptons induces LFV processes such as $\ell_i \to \ell_j \gamma$, $\ell_i \to 3 \ell_j$ and $\mu - e$ conversion in nuclei. This connection between the phenomenology at low-energies and the high-scale mediators is only possible in supersymmetric models and constitutes an excelent opportunity to test the standard seesaw scenario 3 .

In case of high-scale seesaw models, the low-energy theory is simply the MSSM. This allows one to establish definite patterns and hierarchies among the LFV observables. For instance, the branching ratios for the $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$ LFV decays follow the approximate relation [55–57],

$$BR(\ell_i \to 3 \,\ell_j) \simeq \frac{\alpha}{3\pi} \left(\log \left(\frac{m_{\ell_i}^2}{m_{\ell_j}^2} \right) - \frac{11}{4} \right) BR(\ell_i \to \ell_j \gamma).$$
 (3)

Therefore, in supersymmetric high-scale seesaw models, the most constraining LFV process is $\ell_i \to \ell_j \gamma$. The relation in Eq. (3) is caused by the so-called *dipole dominance* in high-scale seesaw models. Among the different contributions to the 3-body decay $\ell_i \to 3 \ell_j$, the dipole photon penguins are the dominant ones, leading to the proportionality between the $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$ branching ratios ⁴.

³In the non-SUSY version of the seesaw mechanism this link between high and low energy scales is lost. In this case probing the origin of neutrino masses becomes a quite challenging task, and only very indirect probes such as neutrinoless double beta decay are possible [54].

⁴An exception to this general rule is found for low pseudoscalar masses and large $\tan \beta$ [58]. In this case, Higgs penguins turn out to be dominant in processes involving the second and third generations, like $\tau \to 3 \mu$. However, this region of parameter space is nowadays under some tension due to strong flavor constraints derived from the observation of quark flavor violating processes like $B_s \to \mu^+\mu^-$ [59].

3.1 Standard high-scale seesaw scenarios

Implementing a high-scale seesaw mechanism in supersymmetric scenarios involves an additional complication. This is related to one of the most appealing features of the MSSM: gauge coupling unification. In case of the type-I seesaw, the introduction of the seesaw mediator does not spoil this attractive feature, since the right-handed neutrino superfields are gauge singlets and do not affect the running of the gauge couplings. In contrast, in the type-II and type-III seesaws, new contributions to the running of the $SU(2)_L$ and $U(1)_Y$ gauge couplings are induced by the seesaw mediators. However, a well-known solution to this problem exists. Unification can be easily restored by embedding the seesaw mediators in full SU(5) multiplets, like 15-plets in the case of type-II [60] or 24-plets [61] in the case of type-III. The contributions from the other members of the multiplet guarantee that the three gauge couplings will eventually meet at a high energy scale, m_{GUT} , although the common value of the coupling changes, g_{GUT} , might be different from that of the MSSM. In addition, note that the 24-plet of SU(5) contains, besides the $SU(2)_L$ triplet, a singlet state which also contributes to neutrino masses. Hence, in this case one actually has a mixture between type-I and type-III seesaws.

The new superfield content, explicitly denoting gauge charges under $SU(3)_c \times SU(2)_L \times U(1)_Y$, and superpotential for each seesaw variant are [62]:

• **Type-I:** Three generations of right-handed neutrino superfields, singlets of SU(5), are introduced, $\widehat{N}^c \sim (1, 1, 0)$.

$$W_I = W_{\text{MSSM}} + Y_{\nu} \hat{N}^c \hat{L} \hat{H}_u + \frac{1}{2} M_R \hat{N}^c \hat{N}^c$$
(4)

• Type-II: In this case one needs to introduce a vector-like pair of 15 and $\overline{15}$ of SU(5), decomposed as $\widehat{S} \sim (6, 1, -2/3)$, $\widehat{T} \sim (1, 3, 1)$ and $\widehat{Z} \sim (3, 2, 1/6)$ (as well as the corresponding bar superfields). \widehat{T} and \widehat{T} are the $SU(2)_L$ triplets responsible for neutrino mass generation.

$$W_{II} = W_{\text{MSSM}} + \frac{1}{\sqrt{2}} (Y_T \widehat{L} \widehat{T} \widehat{L} + Y_S \widehat{d}^c \widehat{S} \widehat{d}^c) + Y_Z \widehat{d}^c \widehat{Z} \widehat{L}$$

$$+ \frac{1}{\sqrt{2}} (\lambda_1 \widehat{H}_d \widehat{T} \widehat{H}_d + \lambda_2 \widehat{H}_u \widehat{T} \widehat{H}_u) + M_T \widehat{T} \widehat{T} + M_Z \widehat{Z} \widehat{Z} + M_S \widehat{S} \widehat{S}$$
 (5)

• **Type-III:** Three generations of **24** of SU(5) are added. They can be decomposed as $\widehat{N}^c \sim (1,1,0)$, $\widehat{G} \sim (8,1,0)$, $\widehat{\Sigma} \sim (1,3,0)$, $\widehat{X} \sim (3,2,-5/6)$ and $\widehat{\overline{X}} \sim (\overline{3},2,5/6)$. As explained above, neutrino masses are generated as a combination of a type-I seesaw (mediated by N^c) and a type-III seesaw (mediate by the $SU(2)_L$ triplet Σ).

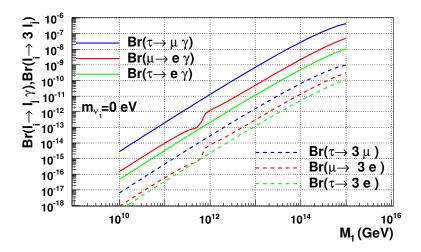


Figure 1: Branching ratios for $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$ as a function of the seesaw scale in the SUSY type-I seesaw. This figure was obtained in the standard SPS1a' point, assuming degenerate right-handed neutrinos and fixing the neutrino Yukawas to reproduce tribimaximal mixing. Furthermore, a massless lightest neutrino was also assumed. Figure taken from [70].

$$W_{III} = W_{\text{MSSM}} + \widehat{H}_u \left(Y_{\Sigma} \widehat{\Sigma} - \sqrt{\frac{3}{10}} Y_{\nu} \widehat{N}^c \right) \widehat{L} + Y_X \widehat{H}_u \widehat{\overline{X}} \widehat{d}^c$$

$$+ \frac{1}{2} M_R \widehat{N}^c \widehat{N}^c + \frac{1}{2} M_G \widehat{G} \widehat{G} + \frac{1}{2} M_{\Sigma} \widehat{\Sigma} \widehat{\Sigma} + M_X \widehat{X} \widehat{\overline{X}}$$

$$(6)$$

The following notation is used in Eqs. (4), (5) and (6): W_{MSSM} is the MSSM superpotential, \hat{H}_d , \hat{H}_u and \hat{L} are the down-Higgs, up-Higgs and lepton $SU(2)_L$ doublet superfields, respectively, and \hat{d}^c is the right-handed down-type quark superfield.

The LFV phenomenology of SUSY seesaw models has been studied by many authors. For the type-I seesaw, low-energy LFV decays such as $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$ have been calculated in [56,57,63–73]. Similarly, $\mu-e$ conversion in nuclei has been studied in [74,75]. The other two seesaw variants have received much less attention. The LFV phenomenology of the SUSY type-II seesaw has been considered in [60,76–81], whereas the SUSY type-III seesaw has been studied in [82–84]. More recently, the interplay between the Higgs mass constraint and LFV was studied in [62] for the three seesaw variants. In the following we comment on some selected results.

Let us first comment on some results for the SUSY type-I seesaw. Fig. 1 shows the ranching ratios for the $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$ decays as a function of the seesaw scale

(the mass of the right-handed neutrino mass). This figure was obtained in Ref. [70], using the standard SPS1a' point [85], assuming degenerate right-handed neutrinos and a massless lightest neutrino and fixing the neutrino Yukawas to reproduce tribimaximal mixing. Although this parameter choice is nowadays excluded for several reasons (the SUSY spectrum is too light to pass the constraints from LHC searches and tribimaximal mixing is now excluded after θ_{13} has been measured), it serves to illustrate the dipole dominance discussed above. Indeed, one sees a perfect correlation between the branching ratios of $\ell_i \to \ell_j \gamma$ and $\ell_i \to 3 \ell_j$, with $\text{BR}(\ell_i \to 3 \ell_j) \ll \text{BR}(\ell_i \to 3 \ell_j)$. As already discussed, this is due to the fact that the photonic dipole operator $(\bar{\ell}_i F_{\mu\nu} \sigma^{\mu\nu} \ell_j)$ dominates both processes.

We now turn of the SUSY type-II seesaw. In the type-II seesaw, the neutrino mass matrix is proportional to the Y_T Yukawa matrix,

$$m_{\nu} = \frac{v_u^2}{2} \frac{\lambda_2}{M_T} Y_T \,. \tag{7}$$

This is derived from the superpotential term $Y_T \widehat{L} \widehat{T} \widehat{L}$ in Eq. (5). This direct relation has important consequences for the phenomenology, since it forces the flavor structure of Y_T to be the same as that of m_{ν} , the latter being measured in neutrino oscillation experiments ⁵. In other words, if all the neutrino masses, angles and phases were known, Y_T would be completely fixed (up to an overall constant). Since Y_T determines the LFV phenomenology, this implies correlations between the neutrino oscillation parameters and LFV observables.

A clear illustration of the previous point is shown in Fig. 2, borrowed from Ref. [77]. By computing the ratios $BR(\ell_i \to \ell_j \gamma)/BR(\ell_m \to \ell_n \gamma)$ one gets rid of the unknown overall factor in the Y_T Yukawas, thus obtaining direct predictions in terms of neutrino parameters. In this case, the figure shows the dependence of these ratios on the mixing angle θ_{13} and the Dirac CP violating phase δ . We see that this scenario is extremely predictive. For example, finding experimentally $BR(\tau \to e\gamma) > BR(\mu \to e\gamma)$ would immediately rule out the model, at least in its minimal form 6 .

Additional ways to test high-scale SUSY seesaws include slepton mass splittings [87] (directly related to LFV) and the study of the SUSY spectrum, usually *deformed* with respect to the standard spectra in constrained (CMSSM) scenarios. In particular, one can construct certain *invariants* that contain information about the high-energy scale, see for example [61, 88, 89]. See also [90] for related ideas.

 $^{^{5}}$ In contrast, in the type-I and type-III seesaws the analogous relation is quadratic in the Yukawa coupling. This introduces extra freedom in the determination of the seesaw parameters (usually encoded in the so-called R matrix [86]) and makes it impossible to predict the Yukawa flavor structure only from neutrino oscillation data.

⁶One way to spoil these strict predictions is to introduce a second $SU(2)_L$ triplet T'. In this case m_{ν} would receive contributions from T and T', $m_{\nu} = m_{\nu}^T + m_{\nu}^{T'}$, and the proportionality in Eq. (7) would be lost.

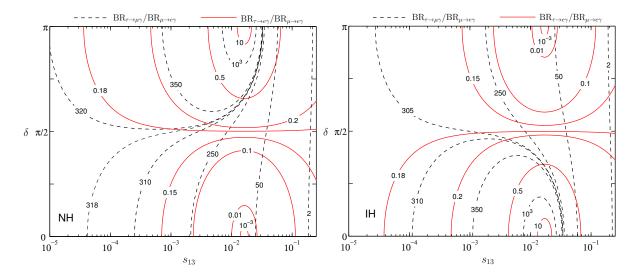


Figure 2: Contours of the ratios $BR(\tau \to \mu \gamma)/BR(\mu \to e \gamma)$ (black, dashed lines) and $BR(\tau \to e \gamma)/BR(\mu \to e \gamma)$ (red, solid lines) in the $(\sin \theta_{13}, \delta)$ plane, for normal hierarchy (on the left) and inverted hierarchy (on the right) for the neutrino mass spectrum. Figure taken from [77].

3.2 Extended high-scale seesaw scenarios

We now turn our attention to extended high-scale SUSY seesaw scenarios beyond the classical type-I, type-II and type-III seesaws. However, before we concentrate on the extended models, let us make a general observation. As already discussed, flavor violating entries in the slepton soft terms $m_{\tilde{L}}^2$ and $m_{\tilde{e}}^2$ (the left and right slepton squared soft masses, respectively) are induced due to their interactions with the seesaw mediators. Even if they are flavor diagonal at the unification scale, off-diagonal terms are generated at low energies by renormalization group running, thus inducing all kinds of LFV processes. In the case of the radiative $\ell_i \to \ell_j \gamma$, the effective dipole operator that contributes to the decay can be written as

$$\mathcal{L}_{\text{dipole}} = e \, \frac{m_{\ell_i}}{2} \, \bar{\ell}_i \sigma_{\mu\nu} F^{\mu\nu} (A_L^{ij} P_L + A_R^{ij} P_R) \ell_j + \text{h.c.} \,, \tag{8}$$

where $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$ are the usual chirality projectors and e the electric charge. The Wilson coefficients A_L and A_R are generated by loops with left and right sleptons, respectively. One finds

$$A_L^{ij} \sim \frac{(m_{\tilde{L}}^2)_{ij}}{M_{SUSY}^4} \quad , \quad A_R^{ij} \sim \frac{(m_{\tilde{e}}^2)_{ij}}{M_{SUSY}^4} \,,$$
 (9)

where it has been assumed that A-terms mixing left-right transitions are negligible. BR($\ell_i \to \ell_j \gamma$) can be computed in terms of A_L and A_R as

$$BR(\ell_i \to \ell_j \gamma) \simeq \frac{48\pi^3 \alpha}{G_F^2} \left(\left| A_L^{ij} \right|^2 + \left| A_R^{ij} \right|^2 \right) BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j), \qquad (10)$$

The straightforward combination of Eqs. (9) and (10) leads to Eq. (1).

Superfield	generations	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
\widehat{Q}	3	3	2	1	$\frac{1}{3}$
\widehat{Q}^c	3	$\bar{3}$	1	2	$-\frac{1}{3}$
\widehat{L}	3	1	2	1	-1
\widehat{L}^c	3	1	1	2	1
$\widehat{\Phi}$	2	1	2	2	0
$\widehat{\Delta}$	1	1	3	1	2
$\widehat{ar{\Delta}}$	1	1	3	1	-2
$\widehat{\Delta}^c$	1	1	1	3	-2
$\widehat{\bar{\Delta}}^c$	1	1	1	3	2
$\widehat{\Omega}$	1	1	3	1	0
$\widehat{\Omega}^c$	1	1	1	3	0

Table 2: LR model. Matter content between the GUT scale and the $SU(2)_R$ breaking scale. The electric charge operator is defined as $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$.

In the minimal SUSY seesaw models discussed above, the seesaw mediators only couple to the left sleptons. For instance, in the type-I case this interaction is given by the superpotential coupling $Y_{\nu}\widehat{L}\widehat{H}_{u}\widehat{N}$, whereas in the type-II case it is given by the $Y_{T}\widehat{L}\widehat{T}\widehat{L}$ term. For this reason, negligible off-diagonal entries in $m_{\tilde{e}}^2$ are induced, implying that minimal SUSY seesaw models predict $A_R \simeq 0$. As we will see below, this has an impact on some low-energy observables that allow, in principle, to test the minimality of the high-scale seesaw mechanism.

Supersymmetric models with non-minimal seesaw mechanisms

As an example supersymmetric model with a non-minimal seesaw mechanisms, we consider the left-right symmetric model of [91,92] (in the following simply called 'the LR model'). The LFV and dark matter phenomenology of this model has been studied in detail in [93,94].

The model is defined below the GUT scale ⁷, where the gauge group is $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. In addition, we assume that parity is conserved. The matter content of the model is given in Tab. 2. Here \widehat{Q} , \widehat{Q}^c , \widehat{L} and \widehat{L}^c are the quark and lepton superfields of the MSSM with the addition of (three) right-handed neutrino superfields to complete the $\widehat{L}^c SU(2)_R$ doublets.

Two $\widehat{\Phi}$ superfields, bidoublets under $SU(2)_L \times SU(2)_R$, are introduced. Among their components, they contain the standard \widehat{H}_d and \widehat{H}_u MSSM Higgs doublets. Finally, the rest of the superfields in Tab. 2 are introduced to break the LR symmetry.

⁷The model implicitly assumes the existence of a GUT model at higher energies. At $m_{\rm GUT}$, the gauge couplings and soft terms unify.

With the representations in Tab. 2, the most general superpotential compatible with the gauge symmetry and parity is

$$W_{LR} = Y_{Q}\widehat{Q}\widehat{\Phi}\widehat{Q}^{c} + Y_{L}\widehat{L}\widehat{\Phi}\widehat{L}^{c} - \frac{\mu}{2}\widehat{\Phi}\widehat{\Phi} + f\widehat{L}\widehat{\Delta}\widehat{L} + f^{*}\widehat{L}^{c}\widehat{\Delta}^{c}\widehat{L}^{c}$$

$$+ a\widehat{\Delta}\widehat{\Omega}\widehat{\Delta} + a^{*}\widehat{\Delta}^{c}\widehat{\Omega}^{c}\widehat{\Delta}^{c} + \alpha\widehat{\Omega}\widehat{\Phi}\widehat{\Phi} + \alpha^{*}\widehat{\Omega}^{c}\widehat{\Phi}\widehat{\Phi}$$

$$+ M_{\Delta}\widehat{\Delta}\widehat{\Delta} + M_{\Delta}^{*}\widehat{\Delta}^{c}\widehat{\Delta}^{c} + M_{\Omega}\widehat{\Omega}\widehat{\Omega} + M_{\Omega}^{*}\widehat{\Omega}^{c}\widehat{\Omega}^{c}.$$

$$(11)$$

Family and gauge indices have been omitted in Eq. (11), more detailed expressions can be found in [91]. Note that this superpotential is invariant under the parity transformations $\widehat{Q} \leftrightarrow (\widehat{Q}^c)^*$, $\widehat{L} \leftrightarrow (\widehat{L}^c)^*$, $\widehat{\Phi} \leftrightarrow \widehat{\Phi}^{\dagger}$, $\widehat{\Delta} \leftrightarrow (\widehat{\Delta}^c)^*$, $\widehat{\Delta} \leftrightarrow (\widehat{\Delta}^c)^*$, $\widehat{\Omega} \leftrightarrow (\widehat{\Omega}^c)^*$. This discrete symmetry reduces the number of free parameters of the model.

The breaking of the left-right gauge group to the MSSM gauge group takes place in two steps: $SU(2)_R \times U(1)_{B-L} \to U(1)_R \times U(1)_{B-L} \to U(1)_Y$. In the first step, the neutral component of the triplet Ω takes a VEV,

$$\langle \Omega^{c\,0} \rangle = \frac{v_R}{\sqrt{2}},\tag{12}$$

which breaks $SU(2)_R$. However, since $I_{3R}(\Omega^{c\,0}) = 0$ there is a $U(1)_R$ symmetry left over. Next, the group $U(1)_R \times U(1)_{B-L}$ is broken by

$$\langle \Delta^{c\,0} \rangle = \frac{v_{BL}}{\sqrt{2}} \;, \qquad \langle \bar{\Delta}^{c\,0} \rangle = \frac{\bar{v}_{BL}}{\sqrt{2}} \;. \tag{13}$$

The remaining symmetry is now $U(1)_Y$ with hypercharge defined as $Y = I_{3R} + \frac{B-L}{2}$.

Regarding neutrino masses, assuming that the left triplets (Δ and $\bar{\Delta}$) have vanishing VEVs, one induces neutrinos masses from a type-I seesaw only thanks to the presence of the right-handed neutrinos [91].

Before discussing how to test this scenario with lepton flavor violation, let us mention some other non-minimal SUSY seesaw models. The phenomenological study in [95] is based on a model very similar to the discussed here, without $\widehat{\Omega}$ superfields. See also [96] for a comprehensive study of supersymmetric models with extended gauge groups at intermediate steps. Finally, the seesaw mechanism can also be embedded in SUSY GUTs, usually leading to very predictive scenarios [97–102].

Probing non-minimal seesaw mechanisms

As already discussed, a pure seesaw model predicts $A_R \simeq 0$ simply because the right sleptons do not couple to the seesaw mediators. However, in models with non-minimal seesaw mechanisms, new interactions between the right sleptons and the members of the extended particle content at high energies might exist. When this is the case, non-zero A_R coefficients can be induced.

Let us consider an example. In the LR model, the left-right symmetry implies that, above the parity breaking scale, the flavor violating entries generated in $m_{\tilde{e}}^2$ are exactly as

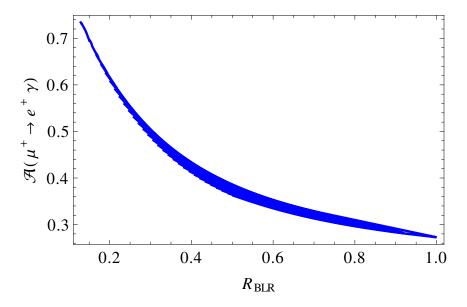


Figure 3: Positron polarization asymmetry $\mathcal{A}(\mu^+ \to e^+ \gamma)$ as a function of the ratio $R_{\rm BLR} = \log(v_R/m_{\rm GUT})/\log(v_{BL}/m_{\rm GUT})$. The seesaw scale M_{SS} has been fixed to 10^{13} GeV, whereas v_{BL} and v_R take values in the ranges $v_{BL} \in [10^{14}, 10^{15}]$ GeV and $v_R \in [10^{15}, 10^{16}]$ GeV. Lighter colours indicate larger v_{BL} . The CMSSM-like parameters have been taken as in the SPS3 benchmark point [85]. Figure taken from [93].

large as the ones in $m_{\tilde{L}}^2$. As a consequence of this, $A_R \neq 0$ is obtained at low energies. In fact, one can even get a handle on the symmetry breaking pattern at high energies. Below the $SU(2)_R$ breaking scale, parity is broken and left and right slepton soft masses evolve differently. The left ones keep running from the $SU(2)_R$ breaking scale to the $U(1)_{B-L}$ scale due to the left slepton couplings with the right-handed neutrinos. One thus expects larger flavor violating effects in the left slepton sector, and the difference between left and right must correlate with the ratio v_{BL}/v_R , which measures the hierarchy between the two breaking scales.

The question is how to measure this difference. For this purpose one can use the positron polarization asymmetry, defined as

$$\mathcal{A}(\mu^+ \to e^+ \gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}.$$
 (14)

If MEG observes $\mu^+ \to e^+ \gamma$ events, the angular distribution of the outgoing positrons can be used to discriminate between left- and right-handed polarized states and measure \mathcal{A} [103, 104]. And this can in turn be used to get information on A_L and A_R .

In a pure SUSY seesaw model one expects $\mathcal{A} \simeq +1$ to a very good accuracy. However, in models with non-minimal seesaw mechanisms \mathcal{A} can significantly depart from +1. For example, the LR model typically leads to significant departures from this expectation, giving an interesting signature of the high-energy restoration of parity. This is shown in Fig. 3, extracted from [93]. First of all, it is clear than the polarization asymmetry

 $\mathcal{A}(\mu^+ \to e^+ \gamma)$ is well correlated with the quantity $\log(v_R/m_{\rm GUT})/\log(v_{BL}/m_{\rm GUT})$. One finds that as v_{BL} and v_R become very different, \mathcal{A} approaches +1. In contrast, when the two breaking scales are close, $v_{BL}/v_R \sim 1$, this effect disappears and the positron polarization asymmetry approaches $\mathcal{A}=0$. Note that a negative value for \mathcal{A} is not possible in this model, since the LFV terms in the right slepton sector never run more than the corresponding terms in the left one.

There are alternative ways to test non-minimal high-scale SUSY seesaw scenarios. These include the study of the SUSY spectrum and, in particular, of the *invariants* pointed out for minimal seesaw models. In this case, they contain information about the high-energy intermediate scales [96, 105]

4 Low-scale seesaw models

The high-scale seesaw has an important drawback: the heaviness of the seesaw mediators precludes any chance of direct tests. Only indirect tests, based on low-energy processes which may have an imprint of the high seesaw scale M_{SS} , are possible, as explained in Sec. 3. In contrast to high-scale models, low-scale seesaw models [106] offer a richer phenomenological perspective since the seesaw mediators are allowed to be light. In this type of neutrino mass models, instead of Eq. (2), neutrino masses are given by

$$m_{\nu} \sim \mu_{\nu} \, \frac{v^2}{M_{SS}^2} \,,$$
 (15)

where M_{SS} is again given by the mass scale of the seesaw mediators and μ_{ν} (not to be confused with the μ parameter of the MSSM) is a small dimensionful parameter, $\mu_{\nu} \ll v, M_{SS}$. In this case, the smallness of neutrino masses is not obtained with a large M_{SS} scale, but with a tiny μ_{ν} parameter. Indeed, if $M_{SS} \sim \text{TeV}$, Eq. (15) implies a μ_{ν} parameter of the order of the eV in order to get m_{ν} in the ~ 0.1 eV ballpark. Therefore, one can simultaneously obtain the correct size of neutrino masses while having seesaw mediators at the TeV scale. This leads to a plethora of new effects, not present in high-scale seesaw models, induced by the *light* seesaw mediators. In particular, novel (and sizable) contributions to LFV processes are possible, sometimes breaking the relation in Eq. (3).

The μ_{ν} parameter is intimately related to the breaking of lepton number. In fact, in the $\mu_{\nu} \to 0$ limit, lepton number is restored and the Majorana neutrino masses in Eq. (15) vanish. This makes the smallness of the μ_{ν} parameter natural, in the sense of 't Hooft [107], since the symmetry of the Lagrangian gets increased when the parameter is set to zero. For this reason, low-scale seesaw models are also said to have almost conserved or slightly broken lepton number.

The collider phenomenology of low-scale seesaw models is much richer than that of high-scale ones. The seesaw mediators can in principle be produced and, through their decays, one may be able to test the mechanism behind neutrino masses. At the LHC, one typically expects multilepton final states, often including missing energy carried away by undetected

neutrinos. In addition, the LFV signatures can be as frequent as the flavor conserving ones. For an imcomplete list of references on the phenomenology of low-scale seesaw models see [108–131]. In the case of a type-I seesaw, the seesaw mediator is a fermionic gauge singlet. This usually suppresses its production in hadronic colliders. However, sizable right-handed neutrino production cross-sections are possible in some type-I seesaw realizations due to the mixing with the left-handed neutrinos, which serves as a portal to the gauge sector. Furthermore, when the type-I seesaw is embedded in a left-right symmetric scenario [132–134] new production mechanisms are possible thanks to the new charged currents mediated by the W_R^{\pm} gauge bosons. This allows for further collider tests or the model, including searches for lepton number violation, see for example [135–141].

We now present the most popular representative of the low-scale seesaw models: the inverse seesaw. For other low-scale seesaw models and their LFV phenomenology see [142–147].

4.1 The supersymmetric inverse seesaw

In the supersymmetric inverse seesaw (ISS) [148–150], the MSSM particle content is extended with 3 generations of right-handed neutrino superfields \hat{N}^c and 3 generations of singlet superfields \hat{X}^{8} . The superpotential takes the form

$$W = W_{\text{MSSM}} + Y_{\nu} \widehat{N}^{c} \widehat{L} \widehat{H}_{u} + M_{R} \widehat{N}^{c} \widehat{X} + \frac{1}{2} \mu_{\nu} \widehat{X} \widehat{X}, \qquad (16)$$

where we have omitted family indices. Y_{ν} and M_R are general 3×3 complex mass matrices and μ_{ν} is a complex symmetric 3×3 matrix. While M_R generates a lepton number conserving Dirac mass term for the fermion singlets, μ_{ν} violates lepton number by two units. This Majorana mass term also leads to a small mass splitting in the heavy neutrino sector, which is then composed by three quasi-Dirac neutrinos. The corresponding soft SUSY breaking Lagrangian is given by

$$-\mathcal{L}^{\text{soft}} = -\mathcal{L}_{\text{MSSM}}^{\text{soft}} + \widetilde{N}^c m_{\widetilde{N}}^2 \widetilde{N}^{c*} + \widetilde{X}^* m_{\widetilde{X}}^2 \widetilde{X} + (T_{\nu} \widetilde{N}^c \widetilde{L} H_u + B_{M_R} \widetilde{N}^c \widetilde{X} + \frac{1}{2} B_{\mu_{\nu}} \widetilde{X} \widetilde{X} + \widetilde{X}^* m_{\widetilde{X}\widetilde{N}}^2 \widetilde{N}^c + \text{h.c.}),$$
 (17)

where B_{M_R} and $B_{\mu\nu}$ are the new parameters involving the scalar superpartners of the singlet neutrino states. Notice that while the former conserves lepton number, the latter violates lepton number by two units. Finally, $\mathcal{L}_{\text{MSSM}}^{\text{soft}}$ contains the soft SUSY breaking terms of the MSSM.

The scalar potential of the model is such that the neutral components of the Higgs superfields get non-zero VEVs,

$$\langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \quad , \quad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}} \,,$$
 (18)

⁸More minimal realizations of the ISS are possible [151–155]. However, for simplicity, we will stick to the most common version with 3 + 3 singlet superfields.

triggering electroweak symmetry breaking (EWSB). This induces mixings in the neutrino sector. In the basis $\nu = (\nu_L, N^c, X)$, the 9×9 neutrino mass matrix is given by

$$\mathcal{M}_{\text{ISS}} = \begin{pmatrix} 0 & m_D^T & 0\\ m_D & 0 & M_R\\ 0 & M_R^T & \mu_{\nu} \end{pmatrix} . \tag{19}$$

where $m_D = \frac{1}{\sqrt{2}} Y_{\nu} v_u$. Assuming the hierarchy $\mu_{\nu} \ll m_D \ll M_R$, the mass matrix \mathcal{M}_{ISS} can be approximately block-diagonalized to give the effective mass matrix for the light neutrinos [156]

$$m_{\text{light}} \simeq m_D^T M_R^{T-1} \mu_{\nu} M_R^{-1} m_D \,.$$
 (20)

On the other hand, the other neutrino states form three heavy quasi-Dirac pairs, with masses corresponding approximately to the entries of M_R .

Eq. (20) has the same form as Eq. (15), with $M_{SS} \sim M_R$. Therefore, by taking a small μ_{ν} parameter, the model allows for small neutrino masses, sizable Y_{ν} Yukawa couplings and singlet neutrinos at the TeV scale (or below).

4.2 LFV in the supersymmetric inverse seesaw

The presence of light singlet neutrinos induces all sorts of effects. Here we will concentrate on their contributions to LFV processes. For some recent works on phenomenological aspects of light singlet neutrinos see [120, 123, 126, 130, 131, 157–165].

There is a vast literature on LFV in models with light singlet neutrinos. Potentially large enhancements, with respect to the usual high-scale models, were already pointed out in early studies [55, 69, 75, 150]. More recently, several works have explored in detail the LFV anatomy of these models, highlighting the relevance of (non-SUSY) box diagrams induced by singlet neutrinos [145, 166-168], computing Higgs penguin contributions [169] and showing enhancements in the usual photon penguin contributions [159]. Regarding purely supersymmetric contributions, the relevance of Z penguins with right sneutrinos was recently readdressed in [170], solving an inconsistency in the analytical results of [57] and [171]. Finally, [172] constitutes the first complete analysis of LFV in the supersymmetric inverse seesaw, taking into account all possible contributions, supersymmetric as well as non-supersymmetric.

We will now present the main results in [172]. These were obtained using FlavorKit [173], a tool that combines the analytical power of SARAH [174–178] with the numerical routines of SPheno [179, 180] to obtain predictions in a wide range of models, based on the automatic computation of the lepton flavor violating observables. See [181] for a comprehensive and pedagogical review of this set of tools.

In the following, we will discuss numerical results obtained using universal boundary conditions at the gauge coupling unification scale, $m_{\rm GUT} \simeq 2 \cdot 10^{16}$ GeV, setting $M_{SUSY} = m_0 = M_{1/2} = -A_0$. In addition, we fixed $B_{\mu_{\nu}} = 100 \,\mu_{\nu}$, $B_{M_R} = 100 \,M_R$, $\tan \beta = 10$, $\mu > 0$ and considered a degenerate singlet spectrum ($M_R^i \equiv M_R$ with i = 1, 2, 3). Furthermore, we fixed the Y_{ν} Yukawa couplings using a modified Casas-Ibarra parameterization [86],

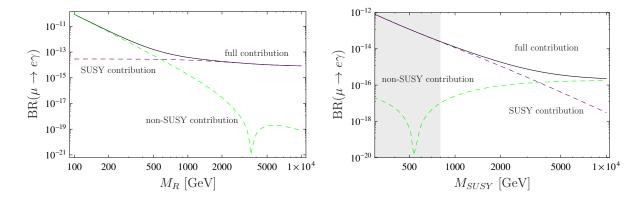


Figure 4: BR($\mu \to e\gamma$) as a function of M_{SUSY} and M_R . On the left-hand side $M_{SUSY}=1$ TeV is fixed, whereas on the right-and side we set $M_R=2$ TeV. The other parameters are given in the text. The gray area roughly corresponds to the parameter space excluded by the LHC SUSY searches. Figure taken from [172].

adapted for the inverse seesaw [157,182], in order to reproduce the neutrino squared mass differences and mixing angles observed in oscillation experiments [183] (see also [7] for an update).

A general conclusion one can draw from [172] is that the LFV phenomenology strongly depends on M_R and M_{SUSY} . The first scale determines the mass of the singlet neutrinos, whereas the second one sets the superparticle masses and their relative size determines the phenomenology. This can be seen in Fig. 4, where $BR(\mu \to e\gamma)$ is shown as a function of M_{SUSY} and M_R . The results are displayed in three curves: the full observable, the SUSY contributions and the non-SUSY ones. The latter consist of contributions from ν - W^{\pm} and ν - H^{\pm} loop diagrams, thus involving the singlet neutrinos in combination with the W boson or a charged Higgs. One finds that the relative weight of SUSY and non-SUSY contributions is given by the hierarchy between these two mass scales. For $M_{SUSY} \gg M_R$, non-SUSY contributions induced by the singlet neutrinos dominate the $\mu \to e\gamma$ amplitude, whereas for $M_{SUSY} \ll M_R$, the usual MSSM contributions generated by chargino/sneutrino and neutralino/slepton loops turn out to be dominant. Moreover, we find that non-SUSY contributions can have strong cancellations.

A similar behavior is found in case of the 3-body decays $\ell_i \to 3 \ell_j$. In Fig. 5 we display numerical results for BR($\mu \to 3 e$) as well as for various contributions to this observable. The anatomy of this decay is more involved, since more types of Feynman diagrams contribute to the amplitude: SUSY and non-SUSY photon, Z and Higgs penguins, as well as box diagrams. As for $\ell_i \to \ell_j \gamma$, we observe that non-SUSY contributions dominate for low M_R ($< M_{SUSY}$). In particular, we see on the left-hand side of Fig. 5 that non-SUSY boxes become completely dominant as soon as one goes to M_R values below ~ 2 TeV. This generic feature was already noted in [145, 166–168]. For higher values of M_R SUSY contributions, and in particular the standard photon dipole penguin, dominate. On the right-hand side we find complementary information, with the different contributions as a

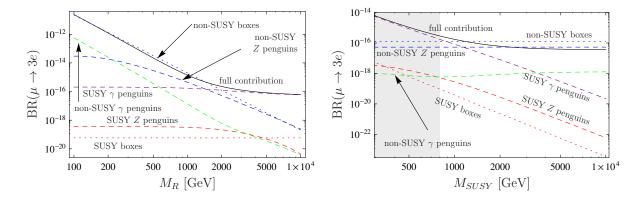


Figure 5: BR($\mu \to 3e$) as a function of M_{SUSY} and M_R . On the left-hand side $M_{SUSY} = 1$ TeV is fixed, whereas on the right-and side we set $M_R = 2$ TeV. The other parameters are given in the text. The gray area roughly corresponds to the parameter space excluded by the LHC SUSY searches. Figure taken from [172].

function of M_{SUSY} for a fixed M_R . It is worth noticing that supersymmetric Z penguins never dominate.

Finally, analogous results are obtained for the $\mu-e$ conversion in nuclei rates. Interestingly, the large non-SUSY boxes found at low M_R break the dipole dominance, leading to a clear departure from Eq. (3). This is illustrated in Fig. 6, where $\text{BR}(\mu \to e\gamma)$, $\text{BR}(\mu \to 3\,e)$ and the $\mu-e$ conversion rates in Ti and Al are shown as a function of M_R . Indeed, for $M_R \lesssim 500$ GeV, the rates for all LFV processes have similar sizes. In this scenario, experiments looking for $\mu \to 3\,e$ and $\mu-e$ conversion in nuclei will soon provide the most stringent constraints in this model.

5 R-parity violating models

The particle content and symmetries of the MSSM allow for the following superpotential terms

$$W^{R_p} = \frac{1}{2} \lambda_{ijk} \widehat{L}_i \widehat{L}_j \widehat{e}_k^c + \lambda'_{ijk} \widehat{L}_i \widehat{Q}_j \widehat{d}_k^c + \epsilon_i \widehat{L}_i \widehat{H}_u$$

$$+ \frac{1}{2} \lambda''_{ijk} \widehat{u}_i^c \widehat{d}_j^c \widehat{d}_k^c ,$$

$$(21)$$

where we have explicitly introduced family indices. Here \hat{u}^c and \hat{e}^c are the right-handed upquark and charged lepton superfields, respectively, and the rest of the superfields have been already defined. The first three terms in W^{R_p} break lepton number (L) whereas the last one breaks baryon number (B). In principle, these couplings are not welcome, since they give rise to many lepton and baryon number violating processes, never observed in nature. For example, the simultaneous presence of the λ' and λ'' couplings would lead to proton decay [184, 185]. This phenomenological problem is solved in the MSSM by introducing by

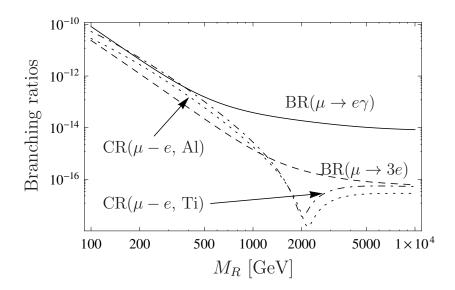


Figure 6: BR($\mu \to e\gamma$), BR($\mu \to 3e$) and $\mu - e$ conversion rates in Ti and Al as a function of M_R . M_{SUSY} is fixed to 1 TeV. The gray area roughly corresponds to the parameter space excluded by the LHC SUSY searches. Figure taken from [172].

hand a new discrete symmetry that forbids all terms in W^{R_p} . This symmetry is known as R-parity [3,4] and is defined as

$$R_p = (-1)^{3(B-L)+2s} \,. \tag{22}$$

Here s is the spin of the particle. It is straightforward to verify that all terms in (21) break R-parity and thus they are forbidden once this symmetry is imposed. The MSSM is defined as R-parity conserving.

However, several arguments can be raised against R-parity:

- R-parity is imposed by hand. Unlike the SM, where L and B conservation is automatic, in the MSSM this has to be forced by introducing a new symmetry, not derived from first principles. This is clearly a step back from the SM.
- R-parity does not solve fast proton decay. It is well known that R-parity does not forbid some dangerous dimension-5 operators that lead to proton decay [186–188]. For example, the operator $\mathcal{O}_5 = \frac{f}{M}\widehat{Q}\widehat{Q}\widehat{Q}\widehat{L}$ has $R_p(\mathcal{O}_5) = +1$ and thus conserves R-parity. The bounds obtained from the non-observation of proton decay imply that, even for $M = M_{\text{Planck}}$, f must be smaller than 10^{-7} [189]. In order to forbid \mathcal{O}_5 and other similar dimension-5 operators, one may resort to additional flavor symmetries [190].
- There is no reason to forbid all the L and B violating operators. Proton decay requires the simultaneous pesence of L and B violating couplings. Therefore,

it is sufficient to impose the conservation of just one of these two symmetries in order to forbid proton decay. This has led to the consideration of alternative discrete symmetries which allow for either L or B violation while protecting the proton. An example of such symmetries is baryon triality (Z_3^B) [186, 191].

Furthermore, there are several good motivations to consider R-parity violating (R_p) scenarios. The violation of lepton number by any of the first three couplings in Eq. (21) automatically leads to non-zero neutrino masses [192–194]. Moreover, the presence of R_p couplings leads to a rich collider phenomenology due to the decay of the LSP. This can be translated into longer decay chains, changing the expected signatures at the LHC [195,196]. In fact, R_p has also been considered as a way to relax the stringent bounds on the squark and gluino masses, see for example [5,6,197,198].

Finally, in R_p the standard neutralino LSP is lost as a dark matter candidate. Therefore, alternative candidates must be considered. Examples in the literature include (i) gravitinos [199–201], (ii) the axion [202,203] or (iii) its superpartner, the axino [204,205]. For general reviews on R-parity violation and collections on bounds on the R_p couplings see [206–209].

We will now discuss separately the LFV phenomenology of two very different supersymmetric scenarios with R-parity violation: explicit R-parity violation (e- R_p) and spontaneous R-parity violation (s- R_p).

5.1 Explicit R-parity violation

The most characteristic signatures of R-parity violating models are, of course, processes with L or B violation. Nevertheless, processes that violate lepton flavor can provide interesting signatures as well and, in fact, they can be more attractive due to the large number of upcoming LFV experiments.

Higgs LFV decays

After the historical discovery of the Higgs boson [1, 2], a lot of effort has been put into the determination of its properties. In particular, the Higgs boson decays may contain a lot of valuable information, with potential indications of new physics. Recently, the CMS collaboration reported on an intriguing 2.4σ excess in the $h \to \tau \mu$ channel [32]. This hint, which translates into BR($h \to \tau \mu$) = $(0.84^{+0.39}_{-0.37})$, is based on the analysis of the 2012 dataset, taken at $\sqrt{s} = 8$ TeV and an integrated luminosity of 19.7 fb⁻¹. This large Higgs LFV 9 branching ratio is quite challenging and most NP models cannot accommodate it [212]. In fact, the flavor conserving Higgs decay $h \to \tau \tau$ has a branching ratio of only $\sim 6\%$, not much higher than the LFV one found by CMS. Although independent confirmation by ATLAS, as well as additional statistics in CMS, would be required in order to promote this hint to the category of evidence of new physics, it is interesting to explore different models in order to determine what type of frameworks can accommodate this signal.

⁹For pioneer works on Higgs LFV decays see [210, 211].

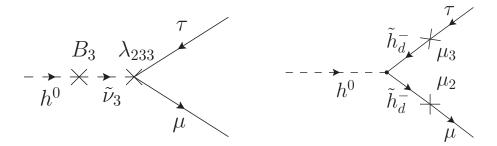


Figure 7: Tree-level R_p contributions to $h \to \tau \mu$. On the left, a $B\lambda$ contribution. On the right, a ϵ_i^2 (denoted as μ_i^2 in [213]) contribution. Figure borrowed from [213].

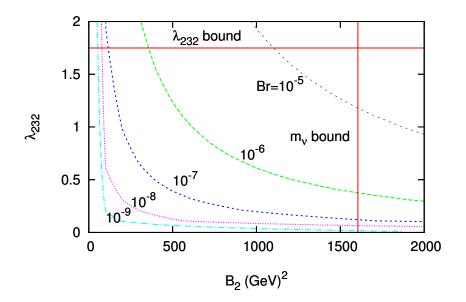


Figure 8: BR($h \to \mu \tau$) contours on the $B_2 - \lambda_{232}$ plane. The continuous horizontal and vertical lines show approximate limits due to neutrino masses (in case of B_2) and charged current experiments (in case of λ_{232}). Figure borrowed from [213].

Regarding supersymmetric models, several scenarios have been recently explored, some of them even before the CMS hint was announced. In particular, the authors of [213,214] considered an extension of the MSSM including all L violating couplings in Eq. (21). The particles-sparticles mixing due to the R_p couplings induce Higgs LFV decays at tree-level, thus potentially being able to reach branching ratios as high as the one found by the CMS collaboration. Two specific examples are shown in Fig. 7. However, the existing experimental bounds on the relevant combinations of R_p couplings contributing to $h \to \infty$ $\tau\mu$ forbid such large LFV branching ratios. For example, in the $B\lambda$ contribution both R_p parameters are strongly constrained. In case of B_i , the R_p mixings between the Higgs boson and the sneutrinos $(\mathcal{L} \supset B_i \widetilde{L}_i H_u)$, they have strong bounds since they induce nonzero neutrino masses [215–217]. Moreover, the λ couplings are constrained by charged current experiments [206]. Once these constraints are taken into account, the maximum $BR(h \to \tau \mu)$ one can get is not very impressive. This is illustrated in Fig. 8, where $BR(h \to \tau \mu)$ contours are drawn on the $B_2 - \lambda_{232}$ plane. From this figure one concludes that BR $(h \to \tau \mu)$ can reach, at most, a few $\times 10^{-5}$, clearly below the CMS hint. Similar conclusions are obtained when other combinations of R_p parameters are considered.

The supersymmetric inverse seesaw has also been considered as a possible setup to reproduce a Higgs LFV branching ratio into $\tau\mu$ at the 1% level [218]. In this case, $h \to \tau\mu$ takes place at 1-loop, naturally suppressing the branching ratio. As a result of this, as well as due to the constraints from other LFV processes such as $\ell_i \to \ell_j \gamma$, one finds that the maximum allowed BR($h \to \tau\mu$) is about $\sim 10^{-5}$. Therefore, this model cannot account for a branching ratio as obtained by CMS either. In order to conclude this discussion on $h \to \tau\mu$ with a positive note, let us mention that known models that can account for BR($h \to \tau\mu$) $\sim 1\%$ exist in the literature. They all involve extended Higgs sectors. In particular, it has been shown that Two-Higgs-Doublet models of type-III, in which both Higgs doublets can couple to up- and down-type fermions, can easily accommodate the CMS signal [212, 219–223]. The MSSM, being a Two-Higgs-Doublet models of type-II, cannot ¹⁰.

Trilinear R-parity violation and LFV

In principle, the usual LFV processes studied in R-parity conserving models can be studied in the R-parity violating ones and, in some cases, they get additional R_p contributions. This is the case of $\ell_i \to 3 \ell_j$, $M \to \ell_i \ell_j$ and $\tau \to M \ell_i$, where M is a neutral meson, which, in the presence of trilinear R_p couplings, can be induced at tree-level [227]. This is represented in Fig. 9, where two examples are shown: $\ell_i \to 3 \ell_j$ induced by λ couplings and sneutrino exchange and $\tau \to M \mu$ induced by λ' couplings and squark exchange. This allows one to derive a large collection of bounds on the size of the trilinear couplings and the masses of the superparticles mediating the LFV decays [228, 229].

Let us consider the right-hand side of Fig. 9. After dressing the quarks in the final

¹⁰In fact, several studies have shown that one cannot accommodate BR($h \to \tau \mu$) $\sim 1\%$ when the low-energy theory is the MSSM [224, 225]. The same conclusion applies to heavy Higgs LFV decays [226].

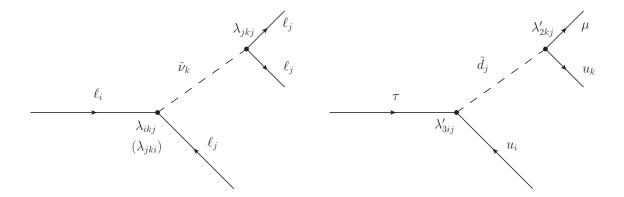


Figure 9: To the left, $\ell_i \to 3 \ell_j$ induced by trilinear λ couplings and sneutrino exchange. To the right, $\tau \to M \mu$ induced by λ' couplings and squark exchange.

state, this Feynman diagram induces $\tau \to M\mu$ at tree-level. Since the exchanged particle, a down-type squark in this case, is much heavier than the rest of particles, this process can be well described by the 4-fermion effective Lagrangian

$$\mathcal{L}_{\text{eff}} = -\frac{\lambda'_{3ij}\lambda'^*_{2kj}}{m^2_{\tilde{d}_i}} \left(\overline{\tau^c}P_L u_i\right) \left(\bar{u}_k P_R \mu^c\right) , \qquad (23)$$

obtained after integrating out the heavy squark. One can now use this Lagrangian and, together with the relevant hadronic form factors, compute rates for processes such as $\tau \to \mu \pi^+ \pi^-$. The authors of [229] followed this method and used Belle results on searches for τ LFV decays [230–232] to obtain the limit

$$\lambda'_{31j}\lambda'^*_{21j} < 2.1 \cdot 10^{-4} \left(\frac{m_{\tilde{d}_j}}{100 \,\text{GeV}}\right)^2$$
 (24)

One can exploit this idea using other LFV observables involving mesons. We refer to [228, 229] for a more complete list of constraints.

Similarly, trilinear R_p couplings can also trigger $\mu-e$ conversion in nuclei, induced by diagrams very similar to the one on the right-hand side of Fig. 9. Interestingly, in this case $\mu-e$ conversion in nuclei would take place at tree-level, while the more popular $\mu\to e\gamma$ would take place at 1-loop. This has been recently pointed out by the authors of [233], who argue that experiments looking for $\mu-e$ conversion in nuclei might be the first (and perhaps the only ones) to observe a non-zero signal in the next round of experiments.

Other results on LFV in R_p scenarios

Before concluding, let us briefly comment on other aspects of LFV in R_p models. An interesting feature of R_p models is that some lepton number violating processes at colliders

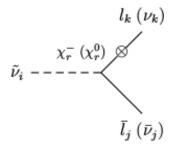


Figure 10: Sneutrino decay to $\ell_k \bar{\ell}_j$ in bilinear R-parity violation. The open circle with a cross indicates the R_p induced mixing between charginos and charged leptons. Figure taken from [234].

might look like lepton flavor violating ones. This is for example the case of sneutrino decay in bilinear R-parity violation [234], as shown in Fig. 10. This process is possible thanks to the mixing between the MSSM charginos and the standard charged leptons. At the LHC, if the sneutrinos are directly produced, the absence of missing energy would make this process look like a LFV one.

Finally, for other recent works on LFV in R_p models see [235–237].

5.2 Spontaneous R-parity violation

A very attractive scenario for LFV is that of spontaneous R-parity violation. When a scalar field oddly charged under R-parity gets a VEV in a theory with a R-parity conserving Lagrangian, R-parity gets spontaneous broken. Here we will concentrate on spontaneous L and R_p violation. Although R-parity is a discrete symmetry, its breaking comes along with the breaking of the continuous global symmetry $U(1)_L$. This implies the existence of a massless Goldstone boson, usually called the majoron (J) [238, 239].

The nature of the majoron is crucial for the phenomenological success of the model. In fact, in the first model with s- R_p [240], the breaking of R-parity was triggered by the VEV of a left-handed sneutrino. This simple setup was eventually excluded since the doublet nature of the majoron leads to conflict with LEP bounds on the Z boson invisible decay width and astrophysical data [203, 241]. However, more refined models where the violation of lepton number is induced by a gauge singlet are perfectly valid possibilities. As a benchmark example of this family we will consider here the model introduced in [242]. For alternative models with gauged lepton number see for example [243–245].

In the model of Ref. [242], the particle content is extended with three additional singlet superfields, namely, $\hat{\nu}^c$, \hat{S} and $\hat{\Phi}$, with lepton number assignments of L=-1,1,0 respectively. By assumption, the Lagrangian of the theory conserves lepton number. Therefore, the superpotential can be written as

$$W_{SRPV} = W_{MSSM} + Y_{\nu} \widehat{L} \widehat{N}^{c} \widehat{H}_{u} - h_{0} \widehat{H}_{d} \widehat{H}_{u} \widehat{\Phi} + h \widehat{\Phi} \widehat{N}^{c} \widehat{S} + \frac{\lambda}{3!} \widehat{\Phi}^{3}.$$
 (25)

For simplicity, one can simply consider one generation of \widehat{N}^c and \widehat{S} superfields. Several scalar fields acquire VEVs after electroweak symmetry breaking. In addition to the usual MSSM Higgs boson VEVs, v_d and v_u , these are $\langle \Phi \rangle = v_\Phi / \sqrt{2}$, $\langle \widetilde{N}^c \rangle = v_R / \sqrt{2}$, $\langle \widetilde{S} \rangle = v_S / \sqrt{2}$ and $\langle \widetilde{\nu}_{Li} \rangle = v_i / \sqrt{2}$. This vacuum configuration breaks lepton number and R-parity. In fact, we notice that $v_R \neq 0$ generates the effective bilinear R_p terms $\epsilon_i = Y_\nu^i v_R / \sqrt{2}$. Furthermore, neglecting $v_i \ll v_R, v_S$, one finds the resulting majoron profile

$$J \simeq \operatorname{Im}\left(\frac{v_S}{V}\widetilde{S} - \frac{v_R}{V}\widetilde{N}^c\right), \tag{26}$$

where $V = \sqrt{v_R^2 + v_S^2}$. Eq. (26) shows that the majoron inherits the singlet nature of the scalar fields that break lepton number with their VEVs, thus suppressing the couplings to the Z boson and evading the stringent LEP bound.

Here we are interested in novel LFV features due to the presence of the majoron ¹¹. This new massless state dramatically changes the phenomenology both at collider and low-energy experiments [248,249]. In particular, it leads to new LFV processes, such as $\mu \to eJ$ or $\mu \to eJ\gamma$. The exotic muon decay $\mu \to eJ$ was first studied in [250] and later revisited in [249], where the decay with an additional photon was also considered. Furthermore, the impact of the majoron on $\mu - e$ conversion in nuclei was discussed in [251] ¹².

The rate of the $\mu \to eJ$ decay is determined by the $e - \mu - J$ coupling, $O_{e\mu J}$, which, in the model under consideration, is of the form $O_{e\mu J} \sim \frac{1}{v_R} \times \text{RPV}$ parameters. This makes us conclude that, in general, one expects large partial muon decay widths to majorons for low v_R . However, currently there are no experiments looking for $\mu \to eJ$ and the current best limit on the branching ratio, $\text{BR}(\mu \to eJ) \lesssim 10^{-5}$, dates back to 1986 [253]. Regarding the decay including a photon, $\mu \to eJ\gamma$, one can profit from the MEG experiment and its search for the more popular channel $\mu \to e\gamma$.

The two branching ratios are related by

$$BR(\mu \to eJ\gamma) = \frac{\alpha}{2\pi} \mathcal{I}(x_{min}, y_{min}) BR(\mu \to eJ).$$
 (27)

Here $\mathcal{I}(x_{min}, y_{min})$ is a 3-body phase space integral defined as

$$\mathcal{I}(x_{min}, y_{min}) = \int dx dy \frac{(x-1)(2-xy-y)}{y^2(1-x-y)},$$
(28)

the dimensionless parameters x, y are defined as

$$x = \frac{2E_e}{m_\mu} \quad , \quad y = \frac{2E_\gamma}{m_\mu} \tag{29}$$

and x_{min} and y_{min} are the minimal electron and photon energies that a given experiment can measure. Indeed, the integral in Eq. (28), which would contain infrarred and collinear divergences, is regularized by the specific choices made by an experiment.

¹¹Another interesting signature present in majoron models is the invisible decay of the Higgs boson, $h \to JJ$ [246, 247].

¹²See also [252] for similar LFV processes in the context of invisible axions.

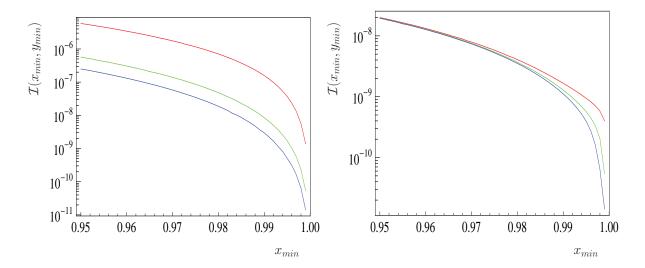


Figure 11: The phase space integral for the decay $\mu \to eJ\gamma$ as a function of x_{min} for three different values of $y_{min} = 0.95, 0.99, 0.995$ from top to bottom and for two different values of $\cos \theta_{e\gamma}$. To the left $\cos \theta_{e\gamma} = -0.99$, whereas to the right $\cos \theta_{e\gamma} = -0.99997$. Figure taken from [249].

As explained above, the main advantage of $\mu \to eJ\gamma$ is the existence of the MEG experiment. However, the question is whether it is sensitive to this exotic LFV process or not. Fig. 11 shows the value of the phase space integral $\mathcal{I}(x_{min}, y_{min})$ as a function of x_{min} for three different values of y_{min} and for two choices of $\cos \theta_{e\gamma}$ (the relative angle between the electron and photon directions). Unfortunately, the MEG experiment is specifically designed for a single search. In fact, the cuts used in the search for $\mu \to e\gamma$ are very restrictive: $x_{min} \ge 0.995$, $y_{min} \ge 0.99$ and $|\pi - \theta_{e\gamma}| \le 8.4$ mrad. For these exact values one finds a tiny phase space integral, $\mathcal{I} \simeq 6 \cdot 10^{-10}$. As a consequence of this, a limit for BR($\mu \to e\gamma$) of the order of $\leq 10^{-13}$ would translate into the useless limit BR($\mu \to e\gamma$) eJ) < 0.14. To improve upon this bound, it is necessary to relax the cuts. For example, by relaxing the cut on the opening angle to $\cos \theta_{e\gamma} = -0.99$. However, this is prone to induce additional unwanted background events. In particular, accidental background from muon annihilation in flight. Therefore, although one could in principle increase the value of the phase space integral $\mathcal{I}(x_{min}, y_{min})$, the background in that case would make the search for a positive signal impossible. This discussion suggests that a better timing resolution of the experiment would be welcome in order to reduce the background and be sensitive to final states including majorons.

6 Summary and conclusions

In summary, we have reviewed the lepton flavor violating phenomenology of several nonminimal supersymmetric models: high-scale and low-scale seesaw models as well as models with explicit or spontaneous R-parity violation. The main conclusion from this overview is that the lepton flavor violating signatures can be very different from those found in the MSSM. This translates into two important messages:

- For the theorists: Lepton flavor violation might be much more intricate than what minimal models predict. Therefore, we should be careful when extrapolating our expectations (derived from the MSSM) to extended frameworks.
- For the experimentalists: Although minimal models are of course well motivated, lepton flavor violation might show up in non-standard channels. We must be ready to avoid missing a relevant signal.

Properly identifying the underlying physics will be crucial in case a positive observation in one or several LFV experiments is made. This problem might be soon have to be addressed, given the exciting projects that are currently going on or soon starting their search for LFV. Hopefully, this review, as well as the many phenomenological studies in the bibliography, will help shedding some light on this matter.

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References

- [1] ATLAS Collaboration Collaboration, G. Aad et al., "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys.Lett. B716 (2012) 1–29, arXiv:1207.7214 [hep-ex].
- [2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," *Phys.Lett.* **B716** (2012) 30–61, arXiv:1207.7235 [hep-ex].
- [3] P. Fayet, "Supergauge Invariant Extension of the Higgs Mechanism and a Model for the electron and Its Neutrino," *Nucl. Phys.* **B90** (1975) 104–124.
- [4] G. R. Farrar and P. Fayet, "Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry," *Phys. Lett.* B76 (1978) 575–579.
- [5] J. A. Evans and Y. Kats, "LHC Coverage of RPV MSSM with Light Stops," JHEP 1304 (2013) 028, arXiv:1209.0764 [hep-ph].

- [6] B. Bhattacherjee, J. L. Evans, M. Ibe, S. Matsumoto, and T. T. Yanagida, "Natural supersymmetrys last hope: R-parity violation via UDD operators," *Phys. Rev.* D87 no. 11, (2013) 115002, arXiv:1301.2336 [hep-ph].
- [7] D. Forero, M. Tortola, and J. Valle, "Neutrino oscillations refitted," *Phys.Rev.* **D90** no. 9, (2014) 093006, arXiv:1405.7540 [hep-ph].
- [8] M. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, "Updated fit to three neutrino mixing: status of leptonic CP violation," *JHEP* 1411 (2014) 052, arXiv:1409.5439 [hep-ph].
- [9] F. Capozzi, G. Fogli, E. Lisi, A. Marrone, D. Montanino, et al., "Status of three-neutrino oscillation parameters, circa 2013," *Phys.Rev.* **D89** no. 9, (2014) 093018, arXiv:1312.2878 [hep-ph].
- [10] S. Petcov, "The Processes $\mu \to e\gamma$, $\mu \to ee\bar{e}$, $\nu' \to \nu\gamma$ in the Weinberg-Salam Model with Neutrino Mixing," Sov. J. Nucl. Phys. **25** (1977) 340.
- [11] T. Cheng and L.-F. Li, "Nonconservation of Separate μ and e-Lepton Numbers in Gauge Theories with V+A Currents," *Phys.Rev.Lett.* **38** (1977) 381.
- [12] S. M. Bilenky, S. Petcov, and B. Pontecorvo, "Lepton Mixing, $\mu \to e + \gamma$ Decay and Neutrino Oscillations," *Phys. Lett.* **B67** (1977) 309.
- [13] Y. Kuno and Y. Okada, "Muon decay and physics beyond the standard model," *Rev.Mod.Phys.* **73** (2001) 151–202, arXiv:hep-ph/9909265 [hep-ph].
- [14] **Particle Data Group** Collaboration, K. Olive *et al.*, "Review of Particle Physics," *Chin. Phys.* C38 (2014) 090001.
- [15] R. H. Bernstein and P. S. Cooper, "Charged Lepton Flavor Violation: An Experimenter's Guide," *Phys.Rept.* **532** (2013) 27–64, arXiv:1307.5787 [hep-ex].
- [16] S. Mihara, J. Miller, P. Paradisi, and G. Piredda, "Charged Lepton Flavor-Violation Experiments," *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 531–552.
- [17] G. Signorelli, "Charged Lepton Flavor Violation Experiments," arXiv:1307.8346 [hep-ex].
- [18] **MEG Collaboration** Collaboration, J. Adam *et al.*, "New constraint on the existence of the $\mu^+ \to e^+ \gamma$ decay," *Phys.Rev.Lett.* **110** (2013) 201801, arXiv:1303.0754 [hep-ex].
- [19] A. Baldini, F. Cei, C. Cerri, S. Dussoni, L. Galli, et al., "MEG Upgrade Proposal," arXiv:1301.7225 [physics.ins-det].
- [20] SINDRUM Collaboration Collaboration, U. Bellgardt *et al.*, "Search for the Decay $mu^+ \rightarrow e^+e^+e^-$," *Nucl. Phys.* B299 (1988) 1.

- [21] A. Blondel, A. Bravar, M. Pohl, S. Bachmann, N. Berger, et al., "Research Proposal for an Experiment to Search for the Decay $\mu \to eee$," arXiv:1301.6113 [physics.ins-det].
- [22] **Mu2e Collaboration** Collaboration, R. Carey *et al.*, "Proposal to search for $\mu^- N \to e^- N$ with a single event sensitivity below 10^{-16} ,".
- [23] **Mu2e Collaboration** Collaboration, D. Glenzinski, "The Mu2e Experiment at Fermilab," *AIP Conf. Proc.* **1222** (2010) 383–386.
- [24] **Mu2e** Collaboration, R. Abrams *et al.*, "Mu2e Conceptual Design Report," arXiv:1211.7019 [physics.ins-det].
- [25] **DeeMe Collaboration** Collaboration, M. Aoki, "A new idea for an experimental search for nu-e conversion," *PoS* **ICHEP2010** (2010) 279.
- [26] **COMET Collaboration** Collaboration, Y. Cui *et al.*, "Conceptual design report for experimental search for lepton flavor violating mu- e- conversion at sensitivity of 10**(-16) with a slow-extracted bunched proton beam (COMET),".
- [27] **COMET** Collaboration, Y. Kuno, "A search for muon-to-electron conversion at J-PARC: The COMET experiment," *PTEP* **2013** (2013) 022C01.
- [28] R. Barlow, "The PRISM/PRIME project," Nucl. Phys. Proc. Suppl. 218 (2011) 44–49.
- [29] T. Aushev, W. Bartel, A. Bondar, J. Brodzicka, T. Browder, et al., "Physics at Super B Factory," arXiv:1002.5012 [hep-ex].
- [30] **BaBar**, **Belle** Collaboration, A. Bevan *et al.*, "The Physics of the *B* Factories," *Eur.Phys.J.* **C74** no. 11, (2014) 3026, arXiv:1406.6311 [hep-ex].
- [31] **LHCb** Collaboration, R. Aaij *et al.*, "Searches for violation of lepton flavour and baryon number in tau lepton decays at LHCb," *Phys.Lett.* **B724** (2013) 36–45, arXiv:1304.4518 [hep-ex].
- [32] **CMS** Collaboration, V. Khachatryan *et al.*, "Search for lepton-flavour-violating decays of the Higgs boson," arXiv:1502.07400 [hep-ex].
- [33] **BaBar Collaboration** Collaboration, B. Aubert *et al.*, "Searches for Lepton Flavor Violation in the Decays $\tau^{\pm} \to e^{\pm} \gamma$ and $\tau^{\pm} \to \mu^{\pm} \gamma$," *Phys.Rev.Lett.* **104** (2010) 021802, arXiv:0908.2381 [hep-ex].
- [34] K. Hayasaka, K. Inami, Y. Miyazaki, K. Arinstein, V. Aulchenko, et al., "Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau-Pairs," Phys. Lett. B687 (2010) 139–143, arXiv:1001.3221 [hep-ex].

- [35] **SINDRUM II Collaboration.** Collaboration, C. Dohmen *et al.*, "Test of lepton flavor conservation in $mu \rightarrow e$ conversion on titanium," *Phys.Lett.* **B317** (1993) 631–636.
- [36] The PRIME working group Collaboration, "Search for the $\mu \to e$ conversion process at an ultimate sensitivity of the order of 10^{-18} with prism." Unpublished; loi to j-parc 50-gev ps, loi-25, http://www-ps.kek.jp/jhf-np/LOIlist/pdf/L25.pdf.
- [37] **SINDRUM II Collaboration** Collaboration, W. H. Bertl *et al.*, "A Search for muon to electron conversion in muonic gold," *Eur. Phys. J.* **C47** (2006) 337–346.
- [38] DeeMe Collaboration, H. Natori, "DeeMe experiment An experimental search for a mu-e conversion reaction at J-PARC MLF," Nucl. Phys. Proc. Suppl. 248-250 (2014) 52-57.
- [39] A. J. Buras, B. Duling, T. Feldmann, T. Heidsieck, and C. Promberger, "Lepton Flavour Violation in the Presence of a Fourth Generation of Quarks and Leptons," *JHEP* **1009** (2010) 104, arXiv:1006.5356 [hep-ph].
- [40] E. Ma, "Pathways to naturally small neutrino masses," *Phys.Rev.Lett.* **81** (1998) 1171–1174, arXiv:hep-ph/9805219 [hep-ph].
- [41] P. Minkowski, " $\mu \to e\gamma$ at a Rate of One Out of 10⁹ Muon Decays?," *Phys.Lett.* **B67** (1977) 421–428.
- [42] T. Yanagida, "in KEK lectures, proceedings of the Workshop on Unified Theory and Baryon Number in the Universe, KEK, edited by O. Sawada and A. Sugamoto," 1979.
- [43] M. Gell-Mann, P. Ramond, and R. Slansky, "Complex Spinors and Unified Theories," Conf. Proc. C790927 (1979) 315-321, arXiv:1306.4669 [hep-th].
- [44] R. N. Mohapatra and G. Senjanovic, "Neutrino Mass and Spontaneous Parity Violation," *Phys.Rev.Lett.* **44** (1980) 912.
- [45] J. Schechter and J. Valle, "Neutrino Masses in SU(2) x U(1) Theories," *Phys. Rev.* D22 (1980) 2227.
- [46] J. Schechter and J. Valle, "Neutrino Decay and Spontaneous Violation of Lepton Number," *Phys. Rev.* **D25** (1982) 774.
- [47] W. Konetschny and W. Kummer, "Nonconservation of Total Lepton Number with Scalar Bosons," *Phys. Lett.* **B70** (1977) 433.
- [48] R. Marshak and R. N. Mohapatra, "Selection Rules for Baryon Number Nonconservation in Gauge Models,".

- [49] G. Lazarides, Q. Shafi, and C. Wetterich, "Proton Lifetime and Fermion Masses in an SO(10) Model," *Nucl. Phys.* **B181** (1981) 287–300.
- [50] R. N. Mohapatra and G. Senjanovic, "Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation," *Phys. Rev.* **D23** (1981) 165.
- [51] T. Cheng and L.-F. Li, "Neutrino Masses, Mixings and Oscillations in SU(2) x U(1) Models of Electroweak Interactions," *Phys.Rev.* **D22** (1980) 2860.
- [52] R. Foot, H. Lew, X. He, and G. C. Joshi, "Seesaw Neutrino Masses Induced by a Triplet of Leptons," Z. Phys. C44 (1989) 441.
- [53] F. Borzumati and A. Masiero, "Large Muon and electron Number Violations in Supergravity Theories," *Phys.Rev.Lett.* **57** (1986) 961.
- [54] F. F. Deppisch, M. Hirsch, and H. Pas, "Neutrinoless Double Beta Decay and Physics Beyond the Standard Model," J. Phys. G39 (2012) 124007, arXiv:1208.0727 [hep-ph].
- [55] A. Ilakovac and A. Pilaftsis, "Flavor violating charged lepton decays in seesaw-type models," *Nucl. Phys.* **B437** (1995) 491, arXiv:hep-ph/9403398 [hep-ph].
- [56] J. Hisano, T. Moroi, K. Tobe, and M. Yamaguchi, "Lepton flavor violation via right-handed neutrino Yukawa couplings in supersymmetric standard model," *Phys. Rev.* D53 (1996) 2442–2459, arXiv:hep-ph/9510309 [hep-ph].
- [57] E. Arganda and M. J. Herrero, "Testing supersymmetry with lepton flavor violating tau and mu decays," *Phys.Rev.* **D73** (2006) 055003, arXiv:hep-ph/0510405 [hep-ph].
- [58] K. Babu and C. Kolda, "Higgs mediated $\tau \to 3 \mu$ in the supersymmetric seesaw model," *Phys. Rev. Lett.* **89** (2002) 241802, arXiv:hep-ph/0206310 [hep-ph].
- [59] **LHCb** Collaboration, R. Aaij *et al.*, "First Evidence for the Decay $B_s^0 \to \mu^+ \mu^-$," *Phys.Rev.Lett.* **110** no. 2, (2013) 021801, arXiv:1211.2674 [hep-ex].
- [60] A. Rossi, "Supersymmetric seesaw without singlet neutrinos: Neutrino masses and lepton flavor violation," *Phys. Rev.* D66 (2002) 075003, arXiv:hep-ph/0207006 [hep-ph].
- [61] M. R. Buckley and H. Murayama, "How can we test seesaw experimentally?," *Phys.Rev.Lett.* **97** (2006) 231801, arXiv:hep-ph/0606088 [hep-ph].
- [62] M. Hirsch, F. Joaquim, and A. Vicente, "Constrained SUSY seesaws with a 125 GeV Higgs," *JHEP* 1211 (2012) 105, arXiv:1207.6635 [hep-ph].

- [63] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, and T. Yanagida, "Lepton flavor violation in the supersymmetric standard model with seesaw induced neutrino masses," *Phys. Lett.* B357 (1995) 579–587, arXiv:hep-ph/9501407 [hep-ph].
- [64] J. R. Ellis, J. Hisano, M. Raidal, and Y. Shimizu, "A New parametrization of the seesaw mechanism and applications in supersymmetric models," *Phys.Rev.* **D66** (2002) 115013, arXiv:hep-ph/0206110 [hep-ph].
- [65] F. Deppisch, H. Pas, A. Redelbach, R. Ruckl, and Y. Shimizu, "Probing the Majorana mass scale of right-handed neutrinos in mSUGRA," *Eur. Phys. J.* C28 (2003) 365-374, arXiv:hep-ph/0206122 [hep-ph].
- [66] S. Petcov, S. Profumo, Y. Takanishi, and C. Yaguna, "Charged lepton flavor violating decays: Leading logarithmic approximation versus full RG results," Nucl. Phys. B676 (2004) 453–480, arXiv:hep-ph/0306195 [hep-ph].
- [67] S. Petcov, T. Shindou, and Y. Takanishi, "Majorana CP-violating phases, RG running of neutrino mixing parameters and charged lepton flavor violating decays," Nucl. Phys. B738 (2006) 219–242, arXiv:hep-ph/0508243 [hep-ph].
- [68] S. Antusch, E. Arganda, M. Herrero, and A. Teixeira, "Impact of theta(13) on lepton flavour violating processes within SUSY seesaw," *JHEP* 0611 (2006) 090, arXiv:hep-ph/0607263 [hep-ph].
- [69] F. Deppisch and J. Valle, "Enhanced lepton flavor violation in the supersymmetric inverse seesaw model," *Phys.Rev.* D72 (2005) 036001, arXiv:hep-ph/0406040 [hep-ph].
- [70] M. Hirsch, J. Valle, W. Porod, J. Romao, and A. Villanova del Moral, "Probing minimal supergravity in type I seesaw with lepton flavour violation at the LHC," *Phys. Rev.* D78 (2008) 013006, arXiv:0804.4072 [hep-ph].
- [71] A. Abada, A. Figueiredo, J. Romao, and A. Teixeira, "Interplay of LFV and slepton mass splittings at the LHC as a probe of the SUSY seesaw," *JHEP* **1010** (2010) 104, arXiv:1007.4833 [hep-ph].
- [72] A. Abada, A. Figueiredo, J. Romao, and A. Teixeira, "Lepton flavour violation: physics potential of a Linear Collider," *JHEP* 1208 (2012) 138, arXiv:1206.2306 [hep-ph].
- [73] A. Figueiredo and A. Teixeira, "Slepton mass splittings and cLFV in the SUSY seesaw in the light of recent experimental results," *JHEP* **1401** (2014) 015, arXiv:1309.7951 [hep-ph].
- [74] E. Arganda, M. Herrero, and A. Teixeira, "mu-e conversion in nuclei within the CMSSM seesaw: Universality versus non-universality," *JHEP* **0710** (2007) 104, arXiv:0707.2955 [hep-ph].

- [75] F. Deppisch, T. Kosmas, and J. Valle, "Enhanced $\mu^ e^-$ conversion in nuclei in the inverse seesaw model," *Nucl. Phys.* **B752** (2006) 80–92, arXiv:hep-ph/0512360 [hep-ph].
- [76] F. Joaquim and A. Rossi, "Gauge and Yukawa mediated supersymmetry breaking in the triplet seesaw scenario," *Phys.Rev.Lett.* 97 (2006) 181801, arXiv:hep-ph/0604083 [hep-ph].
- [77] F. Joaquim and A. Rossi, "Phenomenology of the triplet seesaw mechanism with Gauge and Yukawa mediation of SUSY breaking," *Nucl. Phys.* **B765** (2007) 71–117, arXiv:hep-ph/0607298 [hep-ph].
- [78] M. Hirsch, S. Kaneko, and W. Porod, "Supersymmetric seesaw type. II. LHC and lepton flavour violating phenomenology," *Phys. Rev.* D78 (2008) 093004, arXiv:0806.3361 [hep-ph].
- [79] J. Esteves, S. Kaneko, J. Romao, M. Hirsch, and W. Porod, "Dark matter in minimal supergravity with type-II seesaw," *Phys.Rev.* D80 (2009) 095003, arXiv:0907.5090 [hep-ph].
- [80] F. Joaquim, "Running effects on neutrino parameters and $\ell_i \to \ell_j \gamma$ predictions in the triplet-extended MSSM," *JHEP* **1006** (2010) 079, arXiv:0912.3427 [hep-ph].
- [81] A. Brignole, F. R. Joaquim, and A. Rossi, "Beyond the standard seesaw: Neutrino masses from Kahler operators and broken supersymmetry," *JHEP* 1008 (2010) 133, arXiv:1007.1942 [hep-ph].
- [82] J. Esteves, J. Romao, M. Hirsch, F. Staub, and W. Porod, "Supersymmetric type-III seesaw: lepton flavour violating decays and dark matter," *Phys. Rev.* D83 (2011) 013003, arXiv:1010.6000 [hep-ph].
- [83] A. Abada, A. Figueiredo, J. Romao, and A. Teixeira, "Probing the supersymmetric type III seesaw: LFV at low-energies and at the LHC," *JHEP* 1108 (2011) 099, arXiv:1104.3962 [hep-ph].
- [84] M. Hirsch, W. Porod, C. Weiss, and F. Staub, "Supersymmetric type-III seesaw mechanism: Lepton flavor violation and LHC phenomenology," *Phys. Rev.* D87 no. 1, (2013) 013010, arXiv:1211.0289 [hep-ph].
- [85] B. Allanach, M. Battaglia, G. Blair, M. Carena, A. De Roeck, et al., "The Snowmass points and slopes: Benchmarks for SUSY searches," Eur. Phys. J. C25 (2002) 113–123, arXiv:hep-ph/0202233 [hep-ph].
- [86] J. Casas and A. Ibarra, "Oscillating neutrinos and $\mu \to e\gamma$," Nucl. Phys. **B618** (2001) 171–204, arXiv:hep-ph/0103065 [hep-ph].

- [87] A. J. Buras, L. Calibbi, and P. Paradisi, "Slepton mass-splittings as a signal of LFV at the LHC," *JHEP* **1006** (2010) 042, arXiv:0912.1309 [hep-ph].
- [88] M. Hirsch, L. Reichert, and W. Porod, "Supersymmetric mass spectra and the seesaw scale," *JHEP* 1105 (2011) 086, arXiv:1101.2140 [hep-ph].
- [89] C. Arbelaez, M. Hirsch, and L. Reichert, "Supersymmetric mass spectra and the seesaw type-I scale," *JHEP* 1202 (2012) 112, arXiv:1112.4771 [hep-ph].
- [90] C. Biggio, L. Calibbi, A. Masiero, and S. K. Vempati, "Postcards from oases in the desert: phenomenology of SUSY with intermediate scales," *JHEP* 1208 (2012) 150, arXiv:1205.6817 [hep-ph].
- [91] C. S. Aulakh, K. Benakli, and G. Senjanovic, "Reconciling supersymmetry and left-right symmetry," *Phys.Rev.Lett.* 79 (1997) 2188–2191, arXiv:hep-ph/9703434 [hep-ph].
- [92] C. S. Aulakh, A. Melfo, A. Rasin, and G. Senjanovic, "Supersymmetry and large scale left-right symmetry," *Phys.Rev.* **D58** (1998) 115007, arXiv:hep-ph/9712551 [hep-ph].
- [93] J. Esteves, J. Romao, M. Hirsch, A. Vicente, W. Porod, et al., "LHC and lepton flavour violation phenomenology of a left-right extension of the MSSM," JHEP 1012 (2010) 077, arXiv:1011.0348 [hep-ph].
- [94] J. Esteves, J. Romao, M. Hirsch, W. Porod, F. Staub, et al., "Dark matter and LHC phenomenology in a left-right supersymmetric model," *JHEP* **1201** (2012) 095, arXiv:1109.6478 [hep-ph].
- [95] W. Chao, "Neutrino Masses and Lepton-flavor-violating tau Decays in the Supersymmetric Left-right Model," *Chin.Phys.* **C35** (2011) 214–222, arXiv:0705.4351 [hep-ph].
- [96] C. Arbelaez, R. M. Fonseca, M. Hirsch, and J. C. Romao, "Supersymmetric SO(10)-inspired GUTs with sliding scales," *Phys.Rev.* **D87** no. 7, (2013) 075010, arXiv:1301.6085 [hep-ph].
- [97] L. Calibbi, A. Faccia, A. Masiero, and S. Vempati, "Lepton flavour violation from SUSY-GUTs: Where do we stand for MEG, PRISM/PRIME and a super flavour factory," *Phys.Rev.* **D74** (2006) 116002, arXiv:hep-ph/0605139 [hep-ph].
- [98] L. Calibbi, A. Faccia, A. Masiero, and S. Vempati, "Running U(e3) and BR($\mu \to e \gamma$) in SUSY-GUTs," *JHEP* **0707** (2007) 012, arXiv:hep-ph/0610241 [hep-ph].

- [99] L. Calibbi, M. Frigerio, S. Lavignac, and A. Romanino, "Flavour violation in supersymmetric SO(10) unification with a type II seesaw mechanism," *JHEP* **0912** (2009) 057, arXiv:0910.0377 [hep-ph].
- [100] A. J. Buras, M. Nagai, and P. Paradisi, "Footprints of SUSY GUTs in Flavour Physics," *JHEP* 1105 (2011) 005, arXiv:1011.4853 [hep-ph].
- [101] C. Biggio and L. Calibbi, "Phenomenology of SUSY SU(5) with type I+III seesaw," *JHEP* **1010** (2010) 037, arXiv:1007.3750 [hep-ph].
- [102] L. Calibbi, D. Chowdhury, A. Masiero, K. Patel, and S. Vempati, "Status of supersymmetric type-I seesaw in SO(10) inspired models," *JHEP* **1211** (2012) 040, arXiv:1207.7227.
- [103] Y. Okada, K.-i. Okumura, and Y. Shimizu, " $\mu toe \gamma$ and $\mu \to 3 \, e$ processes with polarized muons and supersymmetric grand unified theories," *Phys.Rev.* **D61** (2000) 094001, arXiv:hep-ph/9906446 [hep-ph].
- [104] J. Hisano, M. Nagai, P. Paradisi, and Y. Shimizu, "Waiting for $\mu \to e\gamma$ from the MEG experiment," *JHEP* **0912** (2009) 030, arXiv:0904.2080 [hep-ph].
- [105] V. De Romeri, M. Hirsch, and M. Malinsky, "Soft masses in SUSY SO(10) GUTs with low intermediate scales," *Phys.Rev.* D84 (2011) 053012, arXiv:1107.3412 [hep-ph].
- [106] S. M. Boucenna, S. Morisi, and J. W. Valle, "The low-scale approach to neutrino masses," *Adv. High Energy Phys.* **2014** (2014) 831598, arXiv:1404.3751 [hep-ph].
- [107] G. 't Hooft, "Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking," NATO Sci. Ser. B 59 (1980) 135.
- [108] F. del Aguila and J. Aguilar-Saavedra, "Distinguishing seesaw models at LHC with multi-lepton signals," *Nucl. Phys.* **B813** (2009) 22–90, arXiv:0808.2468 [hep-ph].
- [109] A. Atre, T. Han, S. Pascoli, and B. Zhang, "The Search for Heavy Majorana Neutrinos," *JHEP* **0905** (2009) 030, arXiv:0901.3589 [hep-ph].
- [110] P. B. Dev and R. Mohapatra, "TeV Scale Inverse Seesaw in SO(10) and Leptonic Non-Unitarity Effects," *Phys.Rev.* **D81** (2010) 013001, arXiv:0910.3924 [hep-ph].
- [111] P. Bhupal Dev and R. Mohapatra, "Electroweak Symmetry Breaking and Proton Decay in SO(10) SUSY-GUT with TeV W(R)," *Phys.Rev.* **D82** (2010) 035014, arXiv:1003.6102 [hep-ph].
- [112] M. Hirsch, M. Malinsky, W. Porod, L. Reichert, and F. Staub, "Hefty MSSM-like light Higgs in extended gauge models," *JHEP* 1202 (2012) 084, arXiv:1110.3037 [hep-ph].

- [113] C.-Y. Chen and P. B. Dev, "Multi-Lepton Collider Signatures of Heavy Dirac and Majorana Neutrinos," *Phys.Rev.* **D85** (2012) 093018, arXiv:1112.6419 [hep-ph].
- [114] H. An, P. B. Dev, Y. Cai, and R. Mohapatra, "Sneutrino Dark Matter in Gauged Inverse Seesaw Models for Neutrinos," *Phys.Rev.Lett.* 108 (2012) 081806, arXiv:1110.1366 [hep-ph].
- [115] V. De Romeri and M. Hirsch, "Sneutrino Dark Matter in Low-scale Seesaw Scenarios," *JHEP* **1212** (2012) 106, arXiv:1209.3891 [hep-ph].
- [116] M. Hirsch, W. Porod, L. Reichert, and F. Staub, "Phenomenology of the minimal supersymmetric $U(1)_{B-L} \times U(1)_R$ extension of the standard model," *Phys.Rev.* **D86** (2012) 093018, arXiv:1206.3516 [hep-ph].
- [117] S. Mondal, S. Biswas, P. Ghosh, and S. Roy, "Exploring novel correlations in trilepton channels at the LHC for the minimal supersymmetric inverse seesaw model," *JHEP* **1205** (2012) 134, arXiv:1201.1556 [hep-ph].
- [118] A. Das and N. Okada, "Inverse seesaw neutrino signatures at the LHC and ILC," *Phys.Rev.* **D88** no. 11, (2013) 113001, arXiv:1207.3734 [hep-ph].
- [119] P. Bhupal Dev, S. Mondal, B. Mukhopadhyaya, and S. Roy, "Phenomenology of Light Sneutrino Dark Matter in cMSSM/mSUGRA with Inverse Seesaw," *JHEP* 1209 (2012) 110, arXiv:1207.6542 [hep-ph].
- [120] P. Bhupal Dev, R. Franceschini, and R. Mohapatra, "Bounds on TeV Seesaw Models from LHC Higgs Data," *Phys.Rev.* **D86** (2012) 093010, arXiv:1207.2756 [hep-ph].
- [121] P. Bandyopadhyay, E. J. Chun, H. Okada, and J.-C. Park, "Higgs Signatures in Inverse Seesaw Model at the LHC," JHEP 1301 (2013) 079, arXiv:1209.4803 [hep-ph].
- [122] P. Bhupal Dev, D. K. Ghosh, N. Okada, and I. Saha, "125 GeV Higgs Boson and the Type-II Seesaw Model," *JHEP* 1303 (2013) 150, arXiv:1301.3453 [hep-ph].
- [123] M. Drewes, "The Phenomenology of Right Handed Neutrinos," *Int.J.Mod.Phys.* **E22** (2013) 1330019, arXiv:1303.6912 [hep-ph].
- [124] J. C. Helo, M. Hirsch, and S. Kovalenko, "Heavy neutrino searches at the LHC with displaced vertices," *Phys.Rev.* **D89** no. 7, (2014) 073005, arXiv:1312.2900 [hep-ph].
- [125] S. Banerjee, P. S. B. Dev, S. Mondal, B. Mukhopadhyaya, and S. Roy, "Invisible Higgs Decay in a Supersymmetric Inverse Seesaw Model with Light Sneutrino Dark Matter," *JHEP* 1310 (2013) 221, arXiv:1306.2143 [hep-ph].

- [126] P. B. Dev, A. Pilaftsis, and U.-k. Yang, "New Production Mechanism for Heavy Neutrinos at the LHC," *Phys.Rev.Lett.* 112 no. 8, (2014) 081801, arXiv:1308.2209 [hep-ph].
- [127] F. F. Deppisch, N. Desai, and J. W. F. Valle, "Is charged lepton flavor violation a high energy phenomenon?," *Phys.Rev.* **D89** no. 5, (2014) 051302, arXiv:1308.6789 [hep-ph].
- [128] J. Aguilar-Saavedra, P. Boavida, and F. Joaquim, "Flavored searches for type-III seesaw mechanism at the LHC," *Phys.Rev.* **D88** (2013) 113008, arXiv:1308.3226 [hep-ph].
- [129] A. Das, P. Bhupal Dev, and N. Okada, "Direct bounds on electroweak scale pseudo-Dirac neutrinos from $\sqrt{s}=8$ TeV LHC data," *Phys.Lett.* **B735** (2014) 364–370, arXiv:1405.0177 [hep-ph].
- [130] F. F. Deppisch, P. S. B. Dev, and A. Pilaftsis, "Neutrinos and Collider Physics," arXiv:1502.06541 [hep-ph].
- [131] S. Banerjee, P. S. B. Dev, A. Ibarra, T. Mandal, and M. Mitra, "Prospects of Heavy Neutrino Searches at Future Lepton Colliders," arXiv:1503.05491 [hep-ph].
- [132] J. C. Pati and A. Salam, "Lepton Number as the Fourth Color," *Phys.Rev.* **D10** (1974) 275–289.
- [133] R. Mohapatra and J. C. Pati, "A Natural Left-Right Symmetry," *Phys.Rev.* **D11** (1975) 2558.
- [134] G. Senjanovic and R. N. Mohapatra, "Exact Left-Right Symmetry and Spontaneous Violation of Parity," *Phys.Rev.* **D12** (1975) 1502.
- [135] W.-Y. Keung and G. Senjanovic, "Majorana Neutrinos and the Production of the Right-handed Charged Gauge Boson," *Phys.Rev.Lett.* **50** (1983) 1427.
- [136] J. Aguilar-Saavedra, F. Deppisch, O. Kittel, and J. Valle, "Flavour in heavy neutrino searches at the LHC," *Phys.Rev.* **D85** (2012) 091301, arXiv:1203.5998 [hep-ph].
- [137] S. Das, F. Deppisch, O. Kittel, and J. Valle, "Heavy Neutrinos and Lepton Flavour Violation in Left-Right Symmetric Models at the LHC," *Phys.Rev.* **D86** (2012) 055006, arXiv:1206.0256 [hep-ph].
- [138] C.-Y. Chen, P. S. B. Dev, and R. Mohapatra, "Probing Heavy-Light Neutrino Mixing in Left-Right Seesaw Models at the LHC," *Phys. Rev.* D88 (2013) 033014, arXiv:1306.2342 [hep-ph].

- [139] A. Maiezza and M. Nemevek, "Strong P invariance, neutron electric dipole moment, and minimal left-right parity at LHC," *Phys.Rev.* **D90** no. 9, (2014) 095002, arXiv:1407.3678 [hep-ph].
- [140] S. Bertolini, A. Maiezza, and F. Nesti, "Present and Future K and B Meson Mixing Constraints on TeV Scale Left-Right Symmetry," *Phys.Rev.* **D89** no. 9, (2014) 095028, arXiv:1403.7112 [hep-ph].
- [141] A. Maiezza, M. Nemevsek, and F. Nesti, "Lepton Number Violation in Higgs Decay," arXiv:1503.06834 [hep-ph].
- [142] A. Abada, C. Biggio, F. Bonnet, M. Gavela, and T. Hambye, "Low energy effects of neutrino masses," *JHEP* **0712** (2007) 061, arXiv:0707.4058 [hep-ph].
- [143] A. Abada, C. Biggio, F. Bonnet, M. Gavela, and T. Hambye, " $\mu \to e\gamma$ and $\tau \to \ell\gamma$ decays in the fermion triplet seesaw model," *Phys.Rev.* **D78** (2008) 033007, arXiv:0803.0481 [hep-ph].
- [144] A. Ibarra, E. Molinaro, and S. Petcov, "Low Energy Signatures of the TeV Scale See-Saw Mechanism," *Phys.Rev.* **D84** (2011) 013005, arXiv:1103.6217 [hep-ph].
- [145] D. Dinh, A. Ibarra, E. Molinaro, and S. Petcov, "The $\mu-e$ Conversion in Nuclei, $\mu \to e\gamma, \mu \to 3e$ Decays and TeV Scale See-Saw Scenarios of Neutrino Mass Generation," *JHEP* **1208** (2012) 125, arXiv:1205.4671 [hep-ph].
- [146] C. G. Cely, A. Ibarra, E. Molinaro, and S. Petcov, "Higgs Decays in the Low Scale Type I See-Saw Model," *Phys. Lett.* **B718** (2013) 957–964, arXiv:1208.3654 [hep-ph].
- [147] D. Dinh and S. Petcov, "Lepton Flavor Violating τ Decays in TeV Scale Type I See-Saw and Higgs Triplet Models," *JHEP* **1309** (2013) 086, arXiv:1308.4311 [hep-ph].
- [148] R. Mohapatra, "Mechanism for Understanding Small Neutrino Mass in Superstring Theories," *Phys. Rev. Lett.* **56** (1986) 561–563.
- [149] R. Mohapatra and J. Valle, "Neutrino Mass and Baryon Number Nonconservation in Superstring Models," *Phys. Rev.* **D34** (1986) 1642.
- [150] J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez, and J. Valle, "Lepton Flavor Nonconservation at High-Energies in a Superstring Inspired Standard Model," *Phys.Lett.* B187 (1987) 303.
- [151] M. Hirsch, T. Kernreiter, J. Romao, and A. Villanova del Moral, "Minimal Supersymmetric Inverse Seesaw: Neutrino masses, lepton flavour violation and LHC phenomenology," *JHEP* 1001 (2010) 103, arXiv:0910.2435 [hep-ph].

- [152] M. Malinsky, T. Ohlsson, Z.-z. Xing, and H. Zhang, "Non-unitary neutrino mixing and CP violation in the minimal inverse seesaw model," *Phys.Lett.* **B679** (2009) 242–248, arXiv:0905.2889 [hep-ph].
- [153] M. Gavela, T. Hambye, D. Hernandez, and P. Hernandez, "Minimal Flavour Seesaw Models," *JHEP* **0909** (2009) 038, arXiv:0906.1461 [hep-ph].
- [154] P. B. Dev and A. Pilaftsis, "Minimal Radiative Neutrino Mass Mechanism for Inverse Seesaw Models," *Phys.Rev.* D86 (2012) 113001, arXiv:1209.4051 [hep-ph].
- [155] A. Abada and M. Lucente, "Looking for the minimal inverse seesaw realisation," Nucl. Phys. B885 (2014) 651–678, arXiv:1401.1507 [hep-ph].
- [156] M. Gonzalez-Garcia and J. Valle, "Fast Decaying Neutrinos and Observable Flavor Violation in a New Class of Majoron Models," *Phys. Lett.* **B216** (1989) 360.
- [157] A. Abada, D. Das, A. Teixeira, A. Vicente, and C. Weiland, "Tree-level lepton universality violation in the presence of sterile neutrinos: impact for R_K and R_{π} ," JHEP~1302~(2013)~048, arXiv:1211.3052 [hep-ph].
- [158] E. Akhmedov, A. Kartavtsev, M. Lindner, L. Michaels, and J. Smirnov, "Improving Electro-Weak Fits with TeV-scale Sterile Neutrinos," *JHEP* 1305 (2013) 081, arXiv:1302.1872 [hep-ph].
- [159] C.-H. Lee, P. Bhupal Dev, and R. Mohapatra, "Natural TeV-scale left-right seesaw mechanism for neutrinos and experimental tests," *Phys.Rev.* **D88** no. 9, (2013) 093010, arXiv:1309.0774 [hep-ph].
- [160] A. Abada, A. Teixeira, A. Vicente, and C. Weiland, "Sterile neutrinos in leptonic and semileptonic decays," *JHEP* **1402** (2014) 091, arXiv:1311.2830 [hep-ph].
- [161] A. Abada, V. De Romeri, and A. Teixeira, "Effect of steriles states on lepton magnetic moments and neutrinoless double beta decay," *JHEP* 1409 (2014) 074, arXiv:1406.6978 [hep-ph].
- [162] S. Antusch and O. Fischer, "Non-unitarity of the leptonic mixing matrix: Present bounds and future sensitivities," JHEP 1410 (2014) 94, arXiv:1407.6607 [hep-ph].
- [163] A. Abada, V. De Romeri, S. Monteil, J. Orloff, and A. Teixeira, "Indirect searches for sterile neutrinos at a high-luminosity Z-factory," arXiv:1412.6322 [hep-ph].
- [164] S. Antusch and O. Fischer, "Testing sterile neutrino extensions of the Standard Model at future lepton colliders," arXiv:1502.05915 [hep-ph].

- [165] M. Drewes and B. Garbrecht, "Experimental and cosmological constraints on heavy neutrinos," arXiv:1502.00477 [hep-ph].
- [166] A. Ilakovac and A. Pilaftsis, "Supersymmetric Lepton Flavour Violation in Low-Scale Seesaw Models," *Phys.Rev.* D80 (2009) 091902, arXiv:0904.2381 [hep-ph].
- [167] R. Alonso, M. Dhen, M. Gavela, and T. Hambye, "Muon conversion to electron in nuclei in type-I seesaw models," *JHEP* 1301 (2013) 118, arXiv:1209.2679 [hep-ph].
- [168] A. Ilakovac, A. Pilaftsis, and L. Popov, "Charged lepton flavor violation in supersymmetric low-scale seesaw models," *Phys.Rev.* **D87** no. 5, (2013) 053014, arXiv:1212.5939 [hep-ph].
- [169] A. Abada, D. Das, and C. Weiland, "Enhanced Higgs Mediated Lepton Flavour Violating Processes in the Supersymmetric Inverse Seesaw Model," *JHEP* 1203 (2012) 100, arXiv:1111.5836 [hep-ph].
- [170] M. E. Krauss, W. Porod, F. Staub, A. Abada, A. Vicente, et al., "Decoupling of heavy sneutrinos in low-scale seesaw models," *Phys.Rev.* **D90** no. 1, (2014) 013008, arXiv:1312.5318 [hep-ph].
- [171] M. Hirsch, F. Staub, and A. Vicente, "Enhancing $l_i \rightarrow 3l_j$ with the Z^0 -penguin," Phys.Rev. **D85** no. 5, (2012) 113013, arXiv:1202.1825 [hep-ph].
- [172] A. Abada, M. E. Krauss, W. Porod, F. Staub, A. Vicente, et al., "Lepton flavor violation in low-scale seesaw models: SUSY and non-SUSY contributions," JHEP 1411 (2014) 048, arXiv:1408.0138 [hep-ph].
- [173] W. Porod, F. Staub, and A. Vicente, "A Flavor Kit for BSM models," *Eur. Phys. J.* C74 no. 8, (2014) 2992, arXiv:1405.1434 [hep-ph].
- [174] F. Staub, "SARAH," arXiv:0806.0538 [hep-ph].
- [175] F. Staub, "From Superpotential to Model Files for FeynArts and CalcHep/CompHep," *Comput.Phys.Commun.* **181** (2010) 1077–1086, arXiv:0909.2863 [hep-ph].
- [176] F. Staub, "Automatic Calculation of supersymmetric Renormalization Group Equations and Self Energies," *Comput. Phys. Commun.* **182** (2011) 808–833, arXiv:1002.0840 [hep-ph].
- [177] F. Staub, "SARAH 3.2: Dirac Gauginos, UFO output, and more," *Comput. Phys. Commun. 184 (2013) pp. 1792–1809, arXiv:1207.0906 [hep-ph].

- [178] F. Staub, "SARAH 4: A tool for (not only SUSY) model builders," *Comput. Phys. Commun. 185 (2014) 1773-1790, arXiv:1309.7223 [hep-ph].
- [179] W. Porod, "SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders," *Comput.Phys.Commun. 153 (2003) 275-315, arXiv:hep-ph/0301101 [hep-ph].
- [180] W. Porod and F. Staub, "SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM," *Comput.Phys.Commun.* **183** (2012) 2458–2469, arXiv:1104.1573 [hep-ph].
- [181] F. Staub, "Exploring new models in all detail with SARAH," arXiv:1503.04200 [hep-ph].
- [182] L. Basso, A. Belyaev, D. Chowdhury, M. Hirsch, S. Khalil, et al., "Proposal for generalised Supersymmetry Les Houches Accord for see-saw models and PDG numbering scheme," Comput. Phys. Commun. 184 (2013) 698-719, arXiv:1206.4563 [hep-ph].
- [183] D. Forero, M. Tortola, and J. Valle, "Global status of neutrino oscillation parameters after Neutrino-2012," *Phys.Rev.* **D86** (2012) 073012, arXiv:1205.4018 [hep-ph].
- [184] I. Hinchliffe and T. Kaeding, "B+L violating couplings in the minimal supersymmetric Standard Model," *Phys.Rev.* **D47** (1993) 279–284.
- [185] P. Nath and P. Fileviez Perez, "Proton stability in grand unified theories, in strings and in branes," *Phys.Rept.* **441** (2007) 191–317, arXiv:hep-ph/0601023 [hep-ph].
- [186] L. E. Ibanez and G. G. Ross, "Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model," *Nucl. Phys.* **B368** (1992) 3–37.
- [187] N. Sakai and T. Yanagida, "Proton Decay in a Class of Supersymmetric Grand Unified Models," *Nucl. Phys.* **B197** (1982) 533.
- [188] S. Weinberg, "Supersymmetry at Ordinary Energies. 1. Masses and Conservation Laws," *Phys. Rev.* **D26** (1982) 287.
- [189] J. R. Ellis, J. Hagelin, D. V. Nanopoulos, and K. Tamvakis, "Observable gravitationally induced baryon decay," *Phys. Lett.* **B124** (1983) 484.
- [190] S. Morisi, E. Peinado, and A. Vicente, "Flavor origin of R-parity," *J.Phys.* **G40** (2013) 085004, arXiv:1212.4145 [hep-ph].
- [191] H. K. Dreiner, C. Luhn, and M. Thormeier, "What is the discrete gauge symmetry of the MSSM?," *Phys.Rev.* **D73** (2006) 075007, arXiv:hep-ph/0512163 [hep-ph].

- [192] L. J. Hall and M. Suzuki, "Explicit R-Parity Breaking in Supersymmetric Models," Nucl. Phys. B231 (1984) 419.
- [193] G. G. Ross and J. Valle, "Supersymmetric Models Without R-Parity," *Phys.Lett.* **B151** (1985) 375.
- [194] M. Hirsch and J. Valle, "Supersymmetric origin of neutrino mass," *New J. Phys.* **6** (2004) 76, arXiv:hep-ph/0405015 [hep-ph].
- [195] H. Dreiner, F. Staub, A. Vicente, and W. Porod, "General MSSM signatures at the LHC with and without R-parity," *Phys.Rev.* **D86** (2012) 035021, arXiv:1205.0557 [hep-ph].
- [196] H. Dreiner, F. Staub, and A. Vicente, "General NMSSM signatures at the LHC," *Phys.Rev.* **D87** no. 3, (2013) 035009, arXiv:1211.6987 [hep-ph].
- [197] P. W. Graham, D. E. Kaplan, S. Rajendran, and P. Saraswat, "Displaced Supersymmetry," *JHEP* 1207 (2012) 149, arXiv:1204.6038 [hep-ph].
- [198] M. Hanussek and J. Kim, "Testing neutrino masses in the R-parity violating minimal supersymmetric standard model with LHC results," *Phys.Rev.* **D85** (2012) 115021, arXiv:1205.0019 [hep-ph].
- [199] S. Borgani, A. Masiero, and M. Yamaguchi, "Light gravitinos as mixed dark matter," *Phys. Lett.* **B386** (1996) 189–197, arXiv:hep-ph/9605222 [hep-ph].
- [200] F. Takayama and M. Yamaguchi, "Gravitino dark matter without R-parity," *Phys.Lett.* **B485** (2000) 388–392, arXiv:hep-ph/0005214 [hep-ph].
- [201] M. Hirsch, W. Porod, and D. Restrepo, "Collider signals of gravitino dark matter in bilinearly broken R-parity," *JHEP* **0503** (2005) 062, arXiv:hep-ph/0503059 [hep-ph].
- [202] J. E. Kim, "Light Pseudoscalars, Particle Physics and Cosmology," *Phys.Rept.* **150** (1987) 1–177.
- [203] G. Raffelt, "Stars as laboratories for fundamental physics,".
- [204] E. J. Chun and H. B. Kim, "Nonthermal axino as cool dark matter in supersymmetric standard model without R-parity," *Phys.Rev.* D60 (1999) 095006, arXiv:hep-ph/9906392 [hep-ph].
- [205] E. J. Chun and H. B. Kim, "Axino Light Dark Matter and Neutrino Masses with R-parity Violation," *JHEP* **0610** (2006) 082, arXiv:hep-ph/0607076 [hep-ph].
- [206] R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, et al., "R-parity violating supersymmetry," *Phys.Rept.* **420** (2005) 1–202, arXiv:hep-ph/0406039 [hep-ph].

- [207] M. Chemtob, "Phenomenological constraints on broken R parity symmetry in supersymmetry models," *Prog.Part.Nucl.Phys.* **54** (2005) 71–191, arXiv:hep-ph/0406029 [hep-ph].
- [208] Y. Kao and T. Takeuchi, "Single-Coupling Bounds on R-parity violating Supersymmetry, an update," arXiv:0910.4980 [hep-ph].
- [209] R. N. Mohapatra, "Supersymmetry and R-parity: an Overview," arXiv:1503.06478 [hep-ph].
- [210] A. Pilaftsis, "Lepton flavor nonconservation in H0 decays," *Phys.Lett.* **B285** (1992) 68–74.
- [211] J. L. Diaz-Cruz and J. Toscano, "Lepton flavor violating decays of Higgs bosons beyond the standard model," *Phys.Rev.* **D62** (2000) 116005, arXiv:hep-ph/9910233 [hep-ph].
- [212] I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik, N. Kosnik, et al., "New Physics Models Facing Lepton Flavor Violating Higgs Decays at the Percent Level," arXiv:1502.07784 [hep-ph].
- [213] A. Arhrib, Y. Cheng, and O. C. Kong, "Higgs to mu+tau Decay in Supersymmetry without R-parity," *Europhys.Lett.* **101** (2013) 31003, arXiv:1208.4669 [hep-ph].
- [214] A. Arhrib, Y. Cheng, and O. C. Kong, "Comprehensive analysis on lepton flavor violating Higgs boson to $\mu^{\mp}\tau^{\pm}$ decay in supersymmetry without R parity," *Phys.Rev.* **D87** no. 1, (2013) 015025, arXiv:1210.8241 [hep-ph].
- [215] Y. Grossman and H. E. Haber, "(S)neutrino properties in R-parity violating supersymmetry. 1. CP conserving phenomena," *Phys.Rev.* **D59** (1999) 093008, arXiv:hep-ph/9810536 [hep-ph].
- [216] E. J. Chun and S. K. Kang, "One loop corrected neutrino masses and mixing in supersymmetric standard model without R-parity," *Phys.Rev.* **D61** (2000) 075012, arXiv:hep-ph/9909429 [hep-ph].
- [217] S. Davidson and M. Losada, "Neutrino masses in the R(p) violating MSSM," *JHEP* 0005 (2000) 021, arXiv:hep-ph/0005080 [hep-ph].
- [218] E. Arganda, M. Herrero, X. Marcano, and C. Weiland, "Imprints of massive inverse seesaw model neutrinos in lepton flavor violating Higgs boson decays," *Phys.Rev.* **D91** no. 1, (2015) 015001, arXiv:1405.4300 [hep-ph].
- [219] S. Davidson and G. J. Grenier, "Lepton flavour violating Higgs and tau to mu gamma," *Phys.Rev.* **D81** (2010) 095016, arXiv:1001.0434 [hep-ph].

- [220] J. Kopp and M. Nardecchia, "Flavor and CP violation in Higgs decays," *JHEP* 1410 (2014) 156, arXiv:1406.5303 [hep-ph].
- [221] D. Aristizabal Sierra and A. Vicente, "Explaining the CMS Higgs flavor violating decay excess," *Phys. Rev.* **D90** no. 11, (2014) 115004, arXiv:1409.7690 [hep-ph].
- [222] J. Heeck, M. Holthausen, W. Rodejohann, and Y. Shimizu, "Higgs $\to \mu \tau$ in Abelian and Non-Abelian Flavor Symmetry Models," arXiv:1412.3671 [hep-ph].
- [223] A. Crivellin, G. D'Ambrosio, and J. Heeck, "Explaining $h \to \mu^{\pm} \tau^{\mp}$, $B \to K^* \mu^+ \mu^-$ and $B \to K \mu^+ \mu^- / B \to K e^+ e^-$ in a two-Higgs-doublet model with gauged $L_{\mu} L_{\tau}$," arXiv:1501.00993 [hep-ph].
- [224] E. Arganda, A. M. Curiel, M. J. Herrero, and D. Temes, "Lepton flavor violating Higgs boson decays from massive seesaw neutrinos," *Phys.Rev.* **D71** (2005) 035011, arXiv:hep-ph/0407302 [hep-ph].
- [225] M. Arana-Catania, E. Arganda, and M. Herrero, "Non-decoupling SUSY in LFV Higgs decays: a window to new physics at the LHC," JHEP 1309 (2013) 160, arXiv:1304.3371 [hep-ph].
- [226] J. Diaz-Cruz, D. K. Ghosh, and S. Moretti, "Lepton Flavour Violating Heavy Higgs Decays Within the nuMSSM and Their Detection at the LHC," *Phys.Lett.* **B679** (2009) 376–381, arXiv:0809.5158 [hep-ph].
- [227] A. de Gouvea, S. Lola, and K. Tobe, "Lepton flavor violation in supersymmetric models with trilinear R-parity violation," *Phys.Rev.* **D63** (2001) 035004, arXiv:hep-ph/0008085 [hep-ph].
- [228] H. Dreiner, M. Kramer, and B. O'Leary, "Bounds on R-parity violating supersymmetric couplings from leptonic and semi-leptonic meson decays," *Phys.Rev.* **D75** (2007) 114016, arXiv:hep-ph/0612278 [hep-ph].
- [229] J. Daub, H. Dreiner, C. Hanhart, B. Kubis, and U. Meissner, "Improving the Hadron Physics of Non-Standard-Model Decays: Example Bounds on R-parity Violation," *JHEP* 1301 (2013) 179, arXiv:1212.4408 [hep-ph].
- [230] **Belle** Collaboration, Y. Miyazaki *et al.*, "Search for Lepton-Flavor-Violating tau Decays into Lepton and f0(980) Meson," *Phys.Lett.* **B672** (2009) 317–322, arXiv:0810.3519 [hep-ex].
- [231] **Belle** Collaboration, Y. Miyazaki *et al.*, "Search for Lepton-Flavor-Violating tau Decays into a Lepton and a Vector Meson," *Phys. Lett.* **B699** (2011) 251–257, arXiv:1101.0755 [hep-ex].

- [232] **Belle** Collaboration, Y. Miyazaki *et al.*, "Search for Lepton-Flavor-Violating and Lepton-Number-Violating $\tau \to \ell h h'$ Decay Modes," *Phys.Lett.* **B719** (2013) 346–353, arXiv:1206.5595 [hep-ex].
- [233] J. Sato and M. Yamanaka, "A way to crosscheck μ -e conversion in the case of no signals of $\mu \to e \gamma$ and $\mu \to 3e$," *Phys.Rev.* **D91** no. 5, (2015) 055018, arXiv:1409.1697 [hep-ph].
- [234] D. Aristizabal Sierra, D. Restrepo, and S. Spinner, "LSP sneutrino decays into heavy standard model pairs," *JHEP* **1305** (2013) 046, arXiv:1212.3310 [hep-ph].
- [235] H.-B. Zhang, T.-F. Feng, S.-M. Zhao, and T.-J. Gao, "Lepton-flavor violation and $(g-2)_{\mu}$ in the $\mu\nu$ SSM," *Erratum-ibid.* **B879** (2014) 235, arXiv:1304.6248 [hep-ph].
- [236] H.-B. Zhang, T.-F. Feng, G.-H. Luo, Z.-F. Ge, and S.-M. Zhao, "Muon conversion to electron in nuclei within the $\mu\nu$ SSM with a 125 GeV Higgs," *JHEP* **1307** (2013) 069, arXiv:1305.4352 [hep-ph].
- [237] R.-M. Wang, J.-H. Sheng, J. Zhu, Y.-Y. Fan, and Y. Gao, "Studying the lepton number and lepton flavor violating $D0 \to e^{\pm}\mu^{\mp}$ and $D_{d/s}^{+} \to \pi(K)^{+}e^{\pm}\mu^{\mp}$ decays," *Int.J.Mod.Phys.* **A29** no. 29, (2014) 1450169.
- [238] Y. Chikashige, R. N. Mohapatra, and R. Peccei, "Are There Real Goldstone Bosons Associated with Broken Lepton Number?," *Phys.Lett.* **B98** (1981) 265.
- [239] G. Gelmini and M. Roncadelli, "Left-Handed Neutrino Mass Scale and Spontaneously Broken Lepton Number," *Phys. Lett.* **B99** (1981) 411.
- [240] C. Aulakh and R. N. Mohapatra, "Neutrino as the Supersymmetric Partner of the Majoron," *Phys. Lett.* **B119** (1982) 136.
- [241] **Particle Data Group** Collaboration, C. Amsler *et al.*, "Review of Particle Physics," *Phys.Lett.* **B667** (2008) 1–1340.
- [242] A. Masiero and J. Valle, "A Model for Spontaneous R Parity Breaking," Phys. Lett. B251 (1990) 273–278.
- [243] M. J. Hayashi and A. Murayama, "Radiative Breaking of $SU(2)_R \times U(1)_{B-L}$ Gauge Symmetry Induced by Broken N=1 Supergravity in a Left-right Symmetric Model," *Phys.Lett.* **B153** (1985) 251.
- [244] P. Fileviez Perez and S. Spinner, "Spontaneous R-Parity Breaking and Left-Right Symmetry," *Phys. Lett.* **B673** (2009) 251–254, arXiv:0811.3424 [hep-ph].
- [245] V. Barger, P. Fileviez Perez, and S. Spinner, "Minimal gauged $U(1)_{B-L}$ model with spontaneous R-parity violation," *Phys.Rev.Lett.* **102** (2009) 181802, arXiv:0812.3661 [hep-ph].

- [246] A. S. Joshipura and J. Valle, "Invisible Higgs decays and neutrino physics," *Nucl. Phys.* **B397** (1993) 105–122.
- [247] M. Hirsch, J. Romao, J. Valle, and A. Villanova del Moral, "Invisible Higgs boson decays in spontaneously broken R-parity," *Phys.Rev.* **D70** (2004) 073012, arXiv:hep-ph/0407269 [hep-ph].
- [248] M. Hirsch, A. Vicente, and W. Porod, "Spontaneous R-parity violation: Lightest neutralino decays and neutrino mixing angles at future colliders," *Phys. Rev.* **D77** (2008) 075005, arXiv:0802.2896 [hep-ph].
- [249] M. Hirsch, A. Vicente, J. Meyer, and W. Porod, "Majoron emission in muon and tau decays revisited," *Phys.Rev.* **D79** (2009) 055023, arXiv:0902.0525 [hep-ph].
- [250] J. Romao, N. Rius, and J. Valle, "Supersymmetric signals in muon and τ decays," Nucl. Phys. **B363** (1991) 369–384.
- [251] X. Garcia i Tormo, D. Bryman, A. Czarnecki, and M. Dowling, "Bounds on majoron emission from muon to electron conversion experiments," *Phys.Rev.* **D84** (2011) 113010, arXiv:1110.2874 [hep-ph].
- [252] A. Celis, J. Fuentes-Martin, and H. Serodio, "An invisible axion model with controlled FCNCs at tree level," *Phys.Lett.* **B741** (2015) 117–123, arXiv:1410.6217 [hep-ph].
- [253] A. Jodidio, B. Balke, J. Carr, G. Gidal, K. Shinsky, et al., "Search for Right-Handed Currents in Muon Decay," Phys. Rev. D34 (1986) 1967.